

XII. Research and Advanced Concepts

PROPULSION DIVISION

N67-29153

A. Breakdown Potentials for Binary Gas Mixtures of Nitrogen-Helium and Helium-Argon,

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1. Introduction

An experimental investigation in the area of gaseous breakdown of a binary gas mixture was undertaken in order to understand more fully the mechanisms involved during the starting phase of an MPD arcjet and an MHD accelerator. Devices of this type generally undergo high electrode erosion rates and periods of instability during the initial phases of operation. Improvements in these areas would provide longer operational lifetimes and higher reliability.

A possible approach to the problem of reducing the deleterious effects of electrode erosion that was taken is the addition of a secondary gas into the flow stream during the starting phase. It was assumed that the configuration of the electrode and other supporting hardware had been established from other constraints. Starting transients and periods of instability are generally associated with a time constant which is much smaller than that which would be associated with the gas flow; therefore, preliminary breakdown investigations were performed under static conditions. The effect of a secondary gas on

the breakdown potential has never been completely described analytically. Certain phenomena, such as the Penning effect, are known to reduce the breakdown potential of a mixture of gases to a potential which is lower than any of the constituents separately. This effect is known to occur whenever the gas, which is the major constituent, has a metastable level higher than the ionization potential of the impurity (minor constituent). Examples of such mixtures are neon-argon, helium-neon, and xenon-rubidium.

Experiments were conducted in order to evaluate breakdown voltage as a function of electrode separation, gas pressure, and constituent concentrations for mixtures of nitrogen-helium and helium-argon by establishing Paschen curves over a wide range of concentrations. Data for pure nitrogen, helium, and argon were also acquired. In order to establish if initial gas purity had an effect on breakdown voltage, both standard (commercial grade) and ultra-high-purity (spectroscopic grade) gases were utilized in the controlled mixtures.

2. Experimental Apparatus and Procedure

Various binary gas mixtures were provided by the mixing system shown schematically in Fig. 1. This gas mixing system was designed for mixing, with high constituent

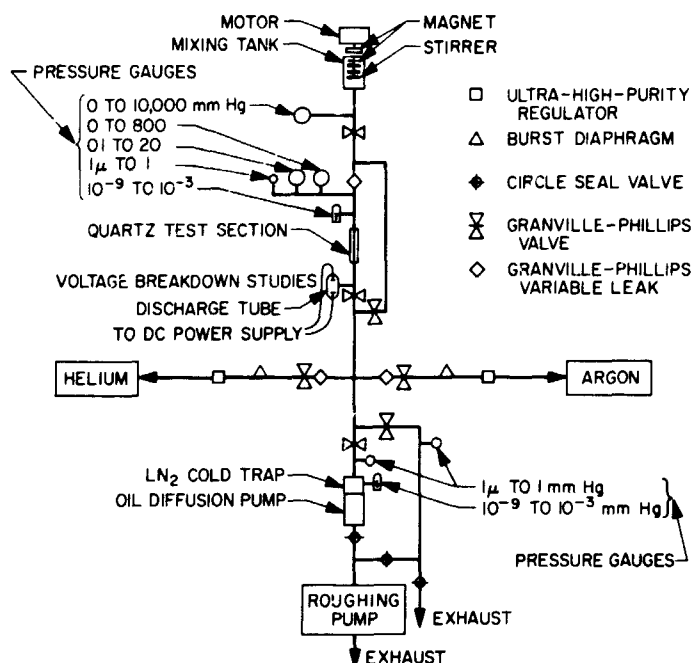


Fig. 1. Gas mixing system

concentration accuracies, any two gases within a concentration range of 0.01 to 100%. Stainless steel construction, in conjunction with ultra-high vacuum valves, minimum O-ring use, and Bourdon tube and aneroid-type pressure gauges were considered essential to ensure mixture purity. However, the selection of the Bourdon tube and aneroid-type pressure gauges restricted the range of pressures that were available. Dalton's law of partial pressures furnished the principle for actual concentration determination. Accuracy of mixture concentration was never less than 1% of the minor constituent within the range of concentrations mentioned above. Incorporated into the mixing system was the experimental discharge tube shown in Fig. 2. This tube consisted of two ultra-high-purity copper disks separated by a 1.9095-in. gap. The two copper surfaces facing each other were flat within 0.0003 and 0.0042 in. and were parallel within 0.0012 in., as determined from the disk centers. The high-voltage, direct-current power supply consisted of a primary controlled transformer used in conjunction with a full-wave rectifier and two 4- μ f capacitors for filtering. The high-voltage limit for this variable supply was approximately 7000 v.

The actual mixing procedure consisted of first evacuating the mixing system to a maximum pressure of 10μ , then purging with the minor constituent. This evacuating and purging procedure was repeated several times with the minor constituent in order to ensure and maintain

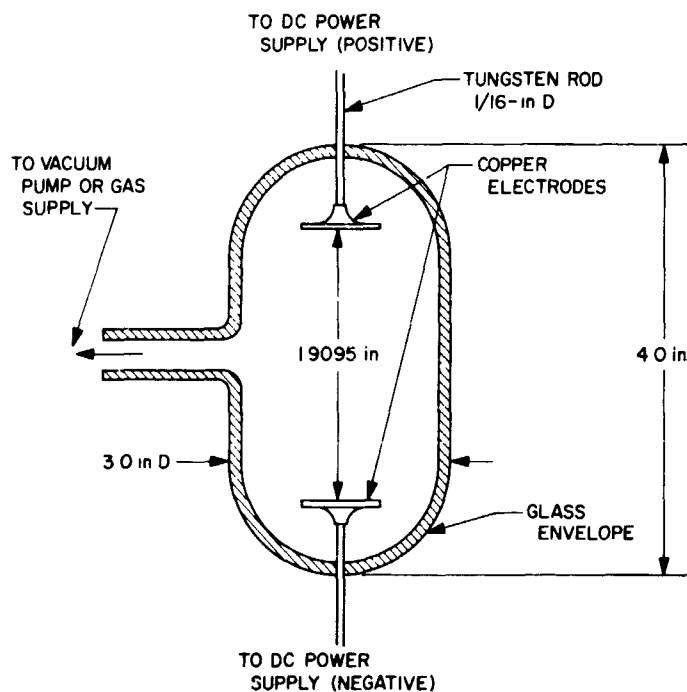


Fig. 2. Discharge tube

high purity levels for the minor constituent. After the minor constituent was placed into the mixing tank (Fig. 1) at the desired pressure, the remainder of the system was completely evacuated to less than 10μ in preparation for adding the major constituent to the mixing tank. The evacuating and purging procedure of the mixing system, excluding the mixing tank, was repeated several times for the major constituent to ensure purity. The final concentration or mixture ratio was computed from the partial pressures of the constituents. The gas mixture was then stored at high pressure in the mixing tank while undergoing forced mixing to provide a homogeneous mixture. This forced mixing was performed by a series of turbine blades (stirrer) located within the mixing tank. The turbine blade shaft was supported on ruby bearings with a magnet at the lower end of the shaft. On the exterior side of the mixing tank, adjacent to the magnet was located another magnet which was positioned on the shaft of a variable speed motor. These magnets provided a magnetic coupling between the turbine blade shaft and the motor shaft. This coupling eliminated the need for a rotating shaft and seal and their resulting contamination. This arrangement of motor and stirrer is shown schematically in Fig. 1. The leak rate of the entire system was approximately 5×10^{-5} ft³/min at 1μ for a total system volume of approximately 0.2 ft³. The mixing tank was helium leak-checked and found to have a leak rate which was negligible for the time periods and pressures concerned.

In order to avoid contamination of the final gas mixture, which was stored at pressures ranging from 1 to 10 atm in the mixing tank, the entire discharge tube and associated plumbing were thoroughly purged in a manner similar to the methods used in the mixing procedure. After thorough purging of the discharge tube and evacuating to a maximum pressure of $10\ \mu$, the test gas was allowed to enter the discharge tube until a pressure of 0.1 mmHg was obtained. This pressure was determined by the criterion of accurate pressure measurements using an aneroid-type pressure gauge. Certainly, other types of gauges are available for measuring pressure at these low regions, but to assure a high gas mixture purity and a reliable measurement, the aneroid type gauges were selected. The limited pressure range of these gauges was not detrimental for the purpose of this investigation but did restrict the determination of the Paschen curve over a wide range of pd (product of pressure and electrode separation). After breakdown information was obtained for the 0.1-mmHg pressure setting, the pressure was increased until breakdown could not be produced with the

available power supply. The actual experimental procedure for producing gaseous breakdown in the discharge tube was to gradually increase the primary voltage of the power supply until breakdown was observed. The breakdown potential was observed on an oscilloscope and recorded on polaroid film. The actual output voltage of the power supply was reduced by the use of a 10,000/1 precision voltage divider before connecting to the oscilloscope. These procedures are similar to those described in SPS 37-43, Vol. IV, pp. 221-223.

3. Results

Data were obtained with two grades of nitrogen and helium in order to demonstrate the effect of gas purity on breakdown potential. This effect is clearly shown in Fig. 3 as a departure of the two curves for the two grades of helium in the high and low regions of pd . This effect was not as apparent for the case of the two grades of nitrogen. The dependence of concentration for a mixture of nitrogen and helium is shown in Fig. 4(a). The cases of pure

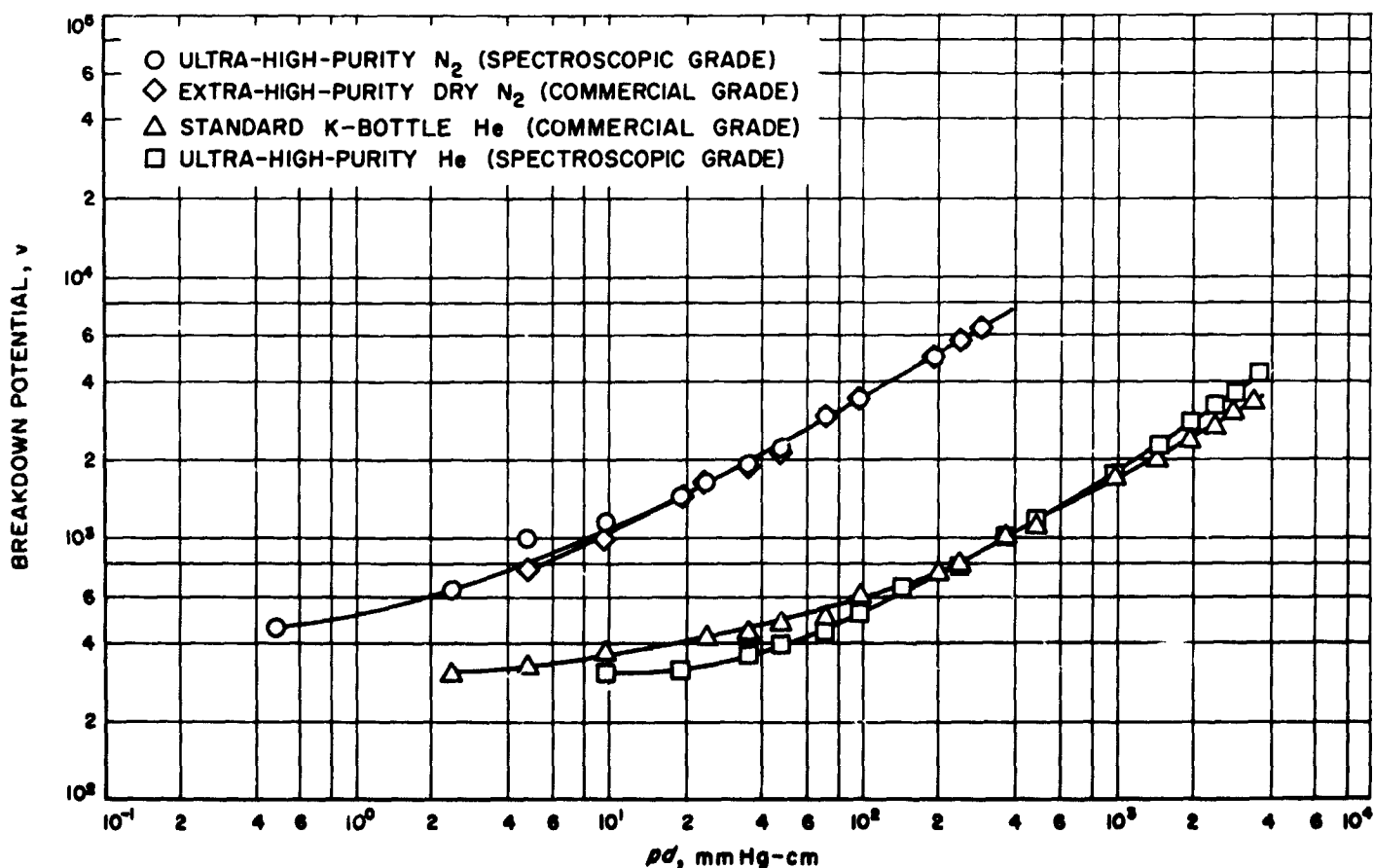


Fig. 3. Breakdown potentials for N_2 and He

nitrogen and pure helium establish the boundaries for this family of curves of breakdown potential as a function of electrode separation, pressure, and concentration. It should be noted that the mean curve of the breakdown potentials between the values for pure nitrogen and pure helium is in the neighborhood of a mixture of 90% helium and 10% nitrogen. These curves demonstrate that a small percentage of nitrogen in a nitrogen-helium mixture has a more dominant effect than a small percentage of helium in a nitrogen-helium mixture.

The experimental data for mixtures of argon and helium are presented in Fig. 4(b). Again the pure gases determine the boundaries for the family of curves for various concentrations, except in the lower regions of pd where it appears that the pure helium curve begins to level off and intercepts the mixture region. This departure from establishing the boundaries might even be expected for the case of nitrogen-helium mixtures in the lower pd regions if it is assumed that nitrogen and air are similar in breakdown characteristics. The intersection of the

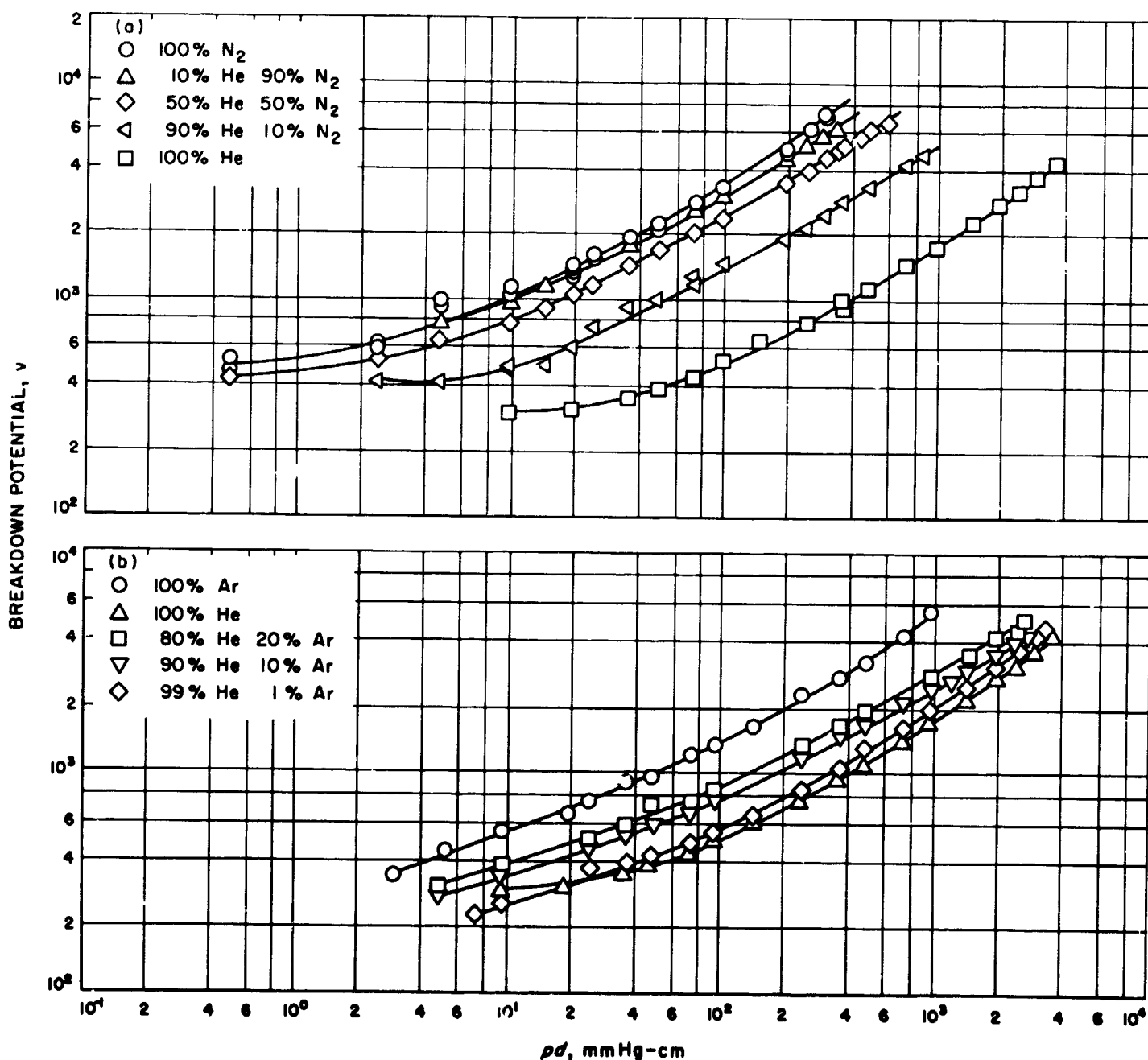


Fig. 4. Breakdown potentials for N_2 and He mixtures

Paschen curves for many pure gases and air is clearly seen in the data given by Druyvestyn and Penning (Ref. 1). A similar result to that exhibited in the nitrogen-helium mixture for the mean curve of the breakdown potential, for a constant product of electrode separation and pressure, is seen for the helium-argon mixture. The pure argon, throughout the pressure range covered in these experiments, always required a higher breakdown potential than the case of pure helium for a constant electrode separation of 1.9095 in. It is interesting to note this fact since, if it were assumed that the ionization potential controlled the breakdown potential, then helium would

have been expected to have the higher breakdown potential. The mean curve of breakdown potential, for a range in concentrations between the extremes is again about 10% argon in 90% helium. Consequently, a slight amount of argon in helium produces a noticeable effect; whereas, a small concentration of helium in argon does not exhibit such a dominating effect. To demonstrate this effect more clearly, two mixture ratios, 0.1 and 5% helium in argon, are shown in Fig. 5. Breakdown voltages were repeatable, for a constant product pd for a given concentration to within approximately 5%, as shown in a typical oscilloscope trace of several breakdown events in Fig. 6. This

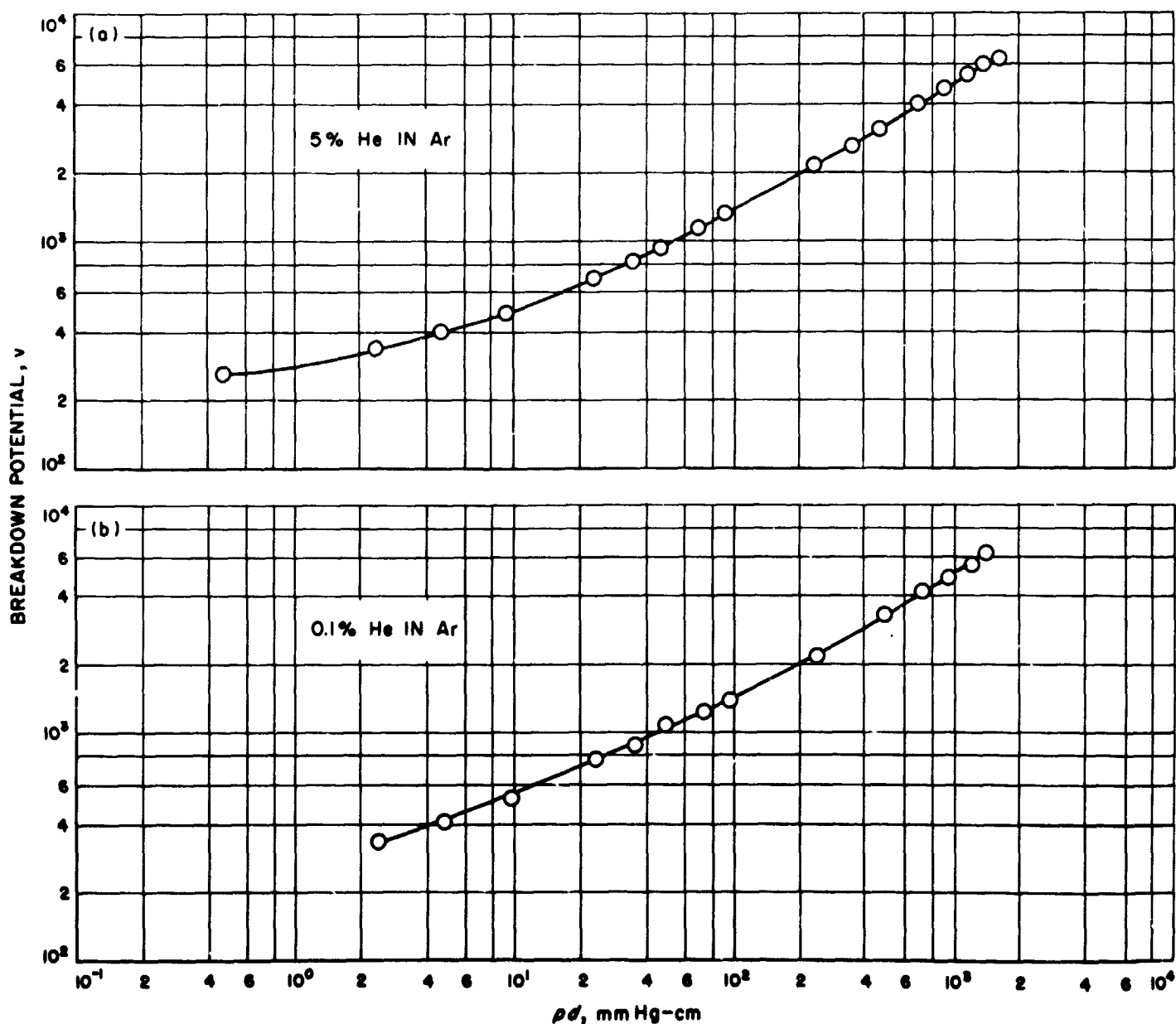


Fig. 5. Breakdown potentials for (a) 5% He in Ar; (b) 0.1% He in Ar

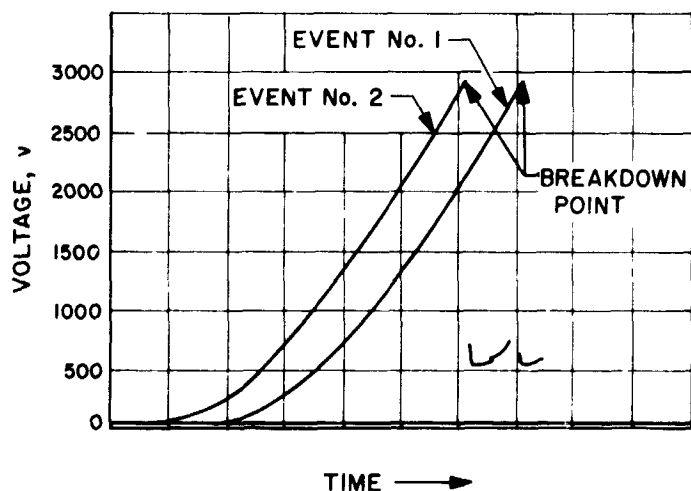


Fig. 6. Typical breakdown voltage-time curve showing two breakdown events for 100% spectroscopic grade N_2 at pd 72 mmHg-cm

figure represents the voltage-time characteristics of the power supply as the primary voltage is increased. At low values of pd on the Paschen curves presented here, the experimental error becomes dominated by pressure gauge errors of approximately 10%.

4. Summary and Conclusions

The effects of a secondary gas on the breakdown potential of the primary component of the resultant mixture were experimentally investigated for gaseous mixtures of nitrogen-helium and helium-argon. The results of this investigation show, for both the nitrogen-helium and helium-argon mixtures, that the breakdown potential does not have a linear relationship with concentration and is evidently not dependent on the ionization potential directly. It has been shown that the breakdown potential of a device operated on argon may be lowered by the addition of helium. This effect would also occur for a device if it were operated on nitrogen and a secondary gas of helium were added. The curves for the nitrogen-helium mixture would also be applicable to a system which has been helium leak-checked, and the effect of residual helium on a nitrogen system environment could be evaluated.

B. Liquid MHD Power Conversion, I. G. Hays, D. J. O'Connor, and G. M. Haskins

The long lifetimes required of electric-propulsion powerplants make systems without rotating parts attractive. A nonrotating Rankine cycle being investigated is

the liquid-metal magnetohydrodynamic system wherein lithium is accelerated by cesium vapor in a two-phase nozzle, separated from the cesium, decelerated in a magnetohydrodynamic generator, and returned through a diffuser and heat source to the nozzle.

A high-temperature corrosion experiment was completed which determined the effect of high flow velocities on the mass transfer of columbium-1% zirconium (Cb-1%Zr) alloy and yttrium oxide by lithium. Examination of the test section after 109 hr at 1141°C had previously revealed (SPS 37-43, Vol. IV, pp. 216-220) that complete dissolution of the yttria test specimens had occurred. The experiment was continued for an additional 391 hr at 1073°C in order that the Cb-1%Zr test specimens would be exposed for 500 hr. This period of time was required to obtain significantly measurable material loss for comparison with theory.

1. Mass Transfer Relations for Simple Dissolution

The mass transfer of wall material into a flowing stream when simple dissolution occurs is described by the conventional relation for fully developed turbulent flow in channels:

$$Sh = 0.023 Re^{0.8} Sc^{0.33} \quad (1)$$

The Sherwood number, which is analogous to the Nusselt number in heat transfer, is given by:

$$Sh = \frac{k_d d_h}{D_r} \quad (2)$$

where

k_d = mass transfer coefficient, cm/sec

d_h = hydraulic diameter, cm

D_r = diffusivity of columbium in lithium, cm^2/sec

The Reynolds number has its usual definition

$$Re = \frac{V d_h}{\nu} \quad (3)$$

where

V = lithium velocity, cm/sec

ν = kinematic viscosity, cm^2/sec

and the Schmidt number Sc is the ratio of ν to D_r .

If k_d is determined from Eq. (1) for given flow conditions and fluid properties, then the mass transfer rate from the wall in g/cm²-sec for the diffusion limited case is

$$\dot{m}_w = k_d \rho_s (C_w - C_b) \quad (4)$$

where

ρ_s = solvent density (g/cm³)

C_w = concentration of solute at wall $\left(\frac{\text{g solute}}{\text{g solvent}} \right)$

C_b = concentration of solute in bulk stream

If the concentrations correspond to the saturated concentration at the wall temperature and the saturated concentration at some other temperature in the system, then for small temperature differences Eq. (4) becomes

$$\Delta t_w = k_d \frac{\rho_s}{\rho_w} \left. \frac{\partial C_s}{\partial T} \right|_{T_w} (T_w - T_e) \tau \quad (5)$$

where

Δt_w = the thickness, cm, lost (or gained) from the wall in a time period τ , sec

ρ_w = density of wall material, g/cm³

C_s = saturated concentration at temperature T , $\frac{\text{g solute}}{\text{g solvent}}$

T_w = wall temperature, °C

T_e = effective concentration temperature in system, °C

Two properties of the columbium-lithium system required in these equations are not well known: D_r and C_s . The diffusivity can be estimated from the Einstein-Stokes relation with reasonable accuracy (Ref. 2):

$$D_r = \frac{kT}{6\pi\mu r_s} \quad (6)$$

where

k = Boltzmann constant

T = temperature, °K

μ = viscosity of solvent, poise

r_s = atomic radius at melting point of solute

$= (3 v_a / 4 \pi N_1)^{1/3}$, cm

v_a = atomic volume at melting point of solute, cm³

N_1 = Avogadro's number

The solubility of columbium in lithium can be estimated from the experimental data of Ref. 3. This data has a spread of greater than one order of magnitude, but the equation for the most reasonable fit is

$$\log_{10} C_s = -2.57 - 1310/T \quad (7)$$

for C_s in weight percent. Hence,

$$\frac{\partial C_s}{\partial T} = \frac{8.06}{T^2} 10^{1.310/T} \quad (8)$$

Over the range of temperatures tested

$$\frac{\partial C_s}{\partial T} \approx 4.8 \times 10^{-7} \% \text{ Cb in Li per } ^\circ\text{C}$$

or for weight fraction,

$$\frac{\partial C_s}{\partial T} = 4.8 \times 10^{-10} \frac{\text{g Cb}}{\text{g Li}} \frac{1}{^\circ\text{C}}$$

2. Prediction of Material Loss for Conditions of Experiment

For the 500-hr experiment the average velocities for the approach piping and the three test specimens were determined to be

$$V_a = 1.6 \text{ m/sec (5.25 ft/sec)}$$

$$V_1 = 19.6 \text{ m/sec (64.3 ft/sec)}$$

$$V_2 = 33.6 \text{ m/sec (110 ft/sec)}$$

$$V_3 = 48.5 \text{ m/sec (159 ft/sec)}$$

The average temperature as determined by pyrometer readings on a hohlraum was 1088°C. The lithium was taken to be saturated with columbium at the temperature of the Cb-1%Zr filter in the system at the base of the reservoir. The location of this filter is indicated in Fig. 7, which shows the test section, reservoir, and piping at 1073°C. The large filter surface area (80 cm²), small pore size (0.25 mm), and highly turbulent vortex flow in the reservoir should provide a sink for all columbium above the saturation concentration.

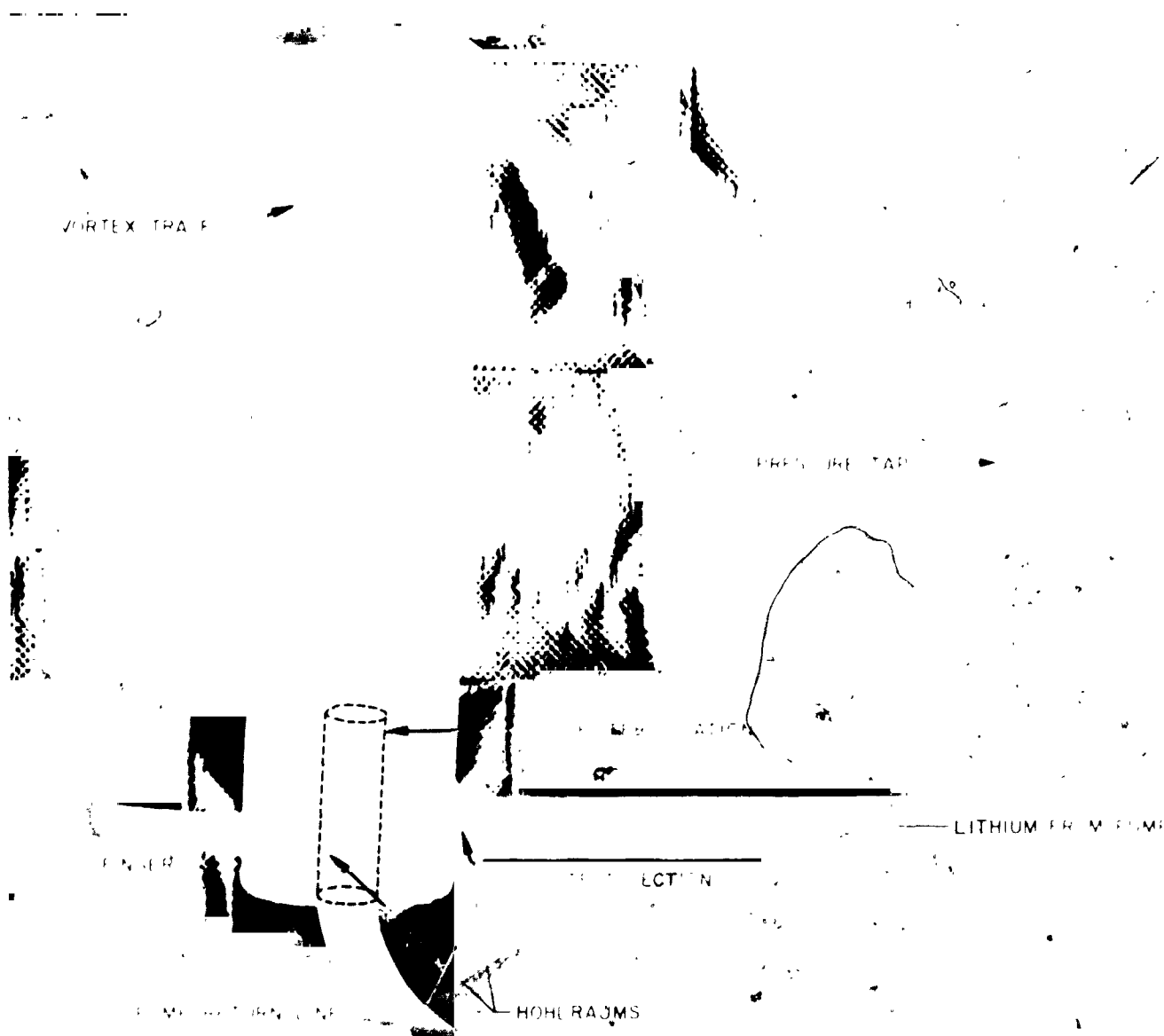


Fig. 7. High-velocity test section and reservoir at 1073°C

The temperature difference was obtained by calculating the heat radiated from the reservoir and then dividing by the product of the lithium mass flow rate and thermal heat capacity

$$\Delta T = \frac{\epsilon_1 \sigma A_1 (T_r^4 - T_c^4) + \epsilon_2 \sigma A_2 (T_r^4 - T_c^4)}{\dot{m}_a c_p}$$

where

ϵ_1 = emissivity of grit-blasted columbium = 0.32 from Ref. 4

σ = Stefan-Boltzmann constant

A_1 = area of reservoir that was grit-blasted

T_c = chamber temperature $\cong 530^\circ\text{K}$

T_w = wall temperature

ϵ_2 = emissivity of as-received columbium = 0.295 from Ref. 4.

A_2 = area of reservoir in as-received state

$\dot{m}_a$ = lithium flow rate = 202 g/sec

c_p = specific heat = 1.0 cal/g $^\circ\text{C}$

Substitution of the appropriate values gives $\Delta T = 7.7^\circ\text{C}$ for the 109-hr period and 7.5°C for the 391-hr period, or an average of 7.5°C . The following properties of lithium at the average temperature were determined from Refs. 5, 6, and 7, respectively:

$$\rho_s = 0.434 \text{ g/cc}$$

$$\mu = 0.15 \text{ centipoise}$$

$$v_a = 10.83 \text{ cm}^2/\text{g-atom}$$

Substitution of these values in Eq. (6) yields

$$D_v = 4.1 \times 10^{-4} \text{ cm}^2/\text{sec}$$

and

$$Sc = \frac{v}{D_v} = 8.7$$

Further use of D_v and Sc in Eqs. (1) and (5) gives the results shown in Table 1 for the 500-hr time period.

The maximum predicted mass loss would be 66.7 microns from the high-velocity wall. More detailed calculations of the increase in concentration of columbium in lithium around the test loop are in progress and are expected to decrease these values by a significant amount.

3. Test Results

The macroscopic appearance of the test specimens before and after 500 hr at an average temperature of 1088°C are shown in Figs. 8 to 14. The closeup pictures reveal that several changes occurred:

- (1) A crystalline deposit was formed in the high-velocity flow channel
- (2) Material removal was minor in the high-velocity, fully developed flow regions.
- (3) Material removal was heavy from the columbium downstream of a cavity left by dissolved yttria. This apparently resulted from local cavitation due to the sharp corner.
- (4) Moderately heavy cracking due to hydrogen embrittlement occurred on all surfaces exposed to lithium as a result of post-test removal treatment with water (Ref. 8).

The deposit was identified by chemical analysis to be yttrium. A photomicrograph showing the top of a crystal and the substrate in the highest velocity region is shown in Fig. 15. These crystals appear to have formed during the 10-hr cooling period after the test was completed from the yttrium previously dissolved in the lithium.

Table 1. Calculated dissolution parameters

Test specimen	d_h , cm	V , ml/sec	Re	Sh	k_d , cm/sec	Δt_w , microns	Δt_w , in.
Approach	1.904	1.6	8.80×10^4	4.25×10^4	0.091	3.0	1.2×10^{-4}
No. 1	0.440	19.6	2.50×10^5	8.05×10^4	0.75	23.9	9.9×10^{-4}
No. 2	0.362	33.6	3.62×10^5	1.24×10^5	1.40	46.5	1.8×10^{-3}
No. 3	0.308	48.5	4.32×10^5	1.52×10^5	2.02	66.7	2.5×10^{-3}

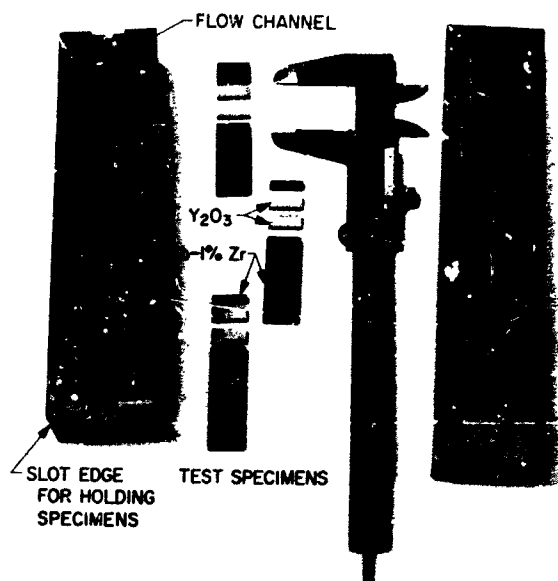


Fig. 8. Test section unassembled prior to welding

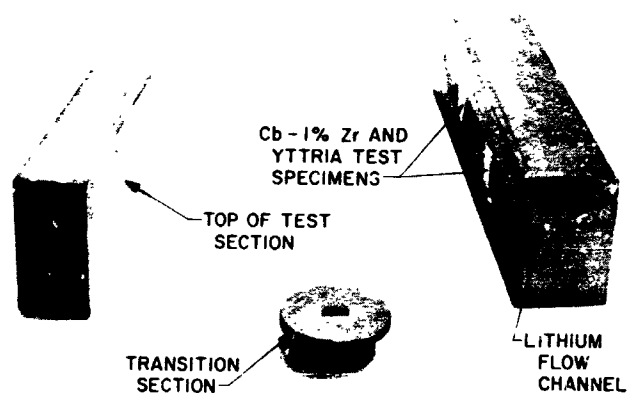


Fig. 9. Test section assembled prior to welding

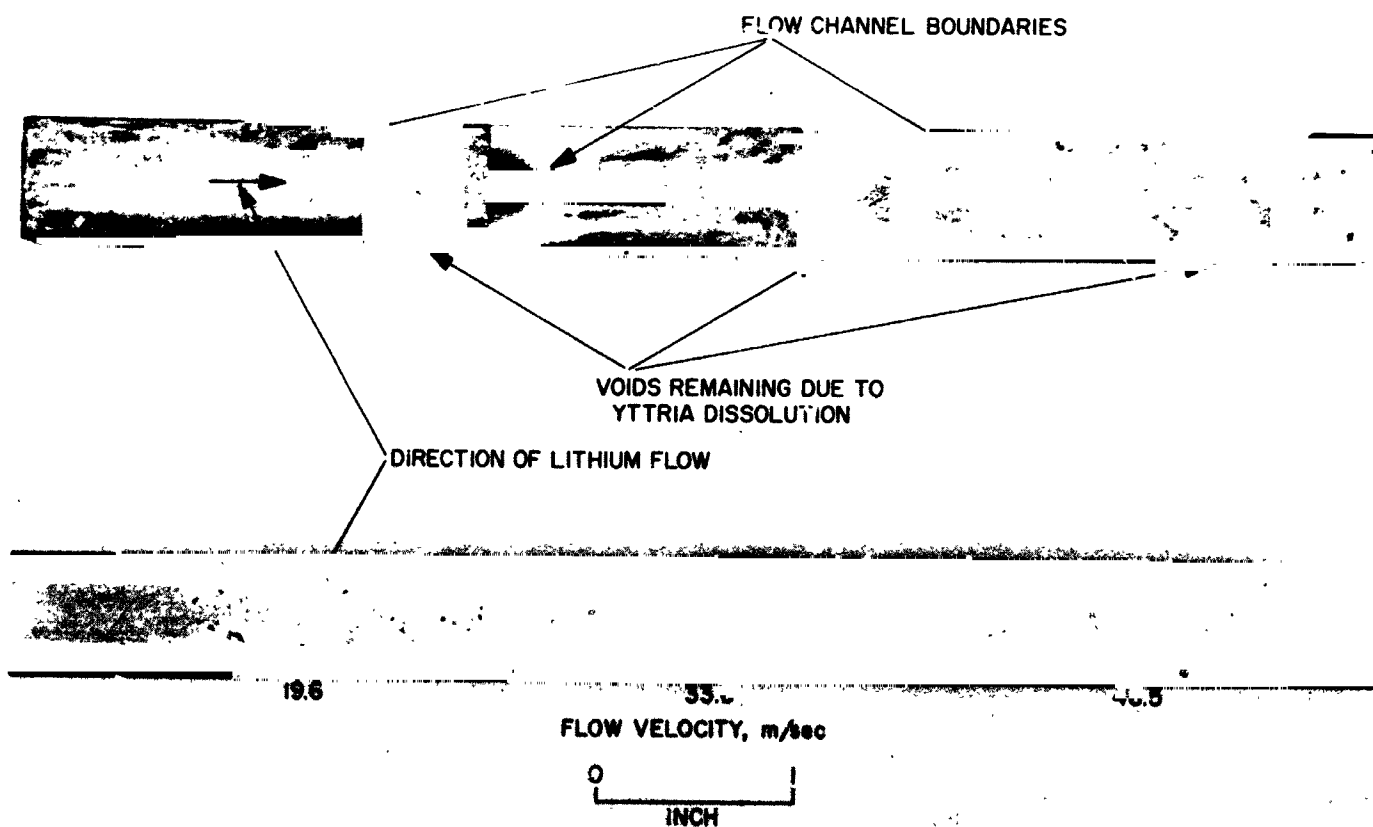


Fig. 10. Test section disassembled after 500 hr at 1088°C average temperature

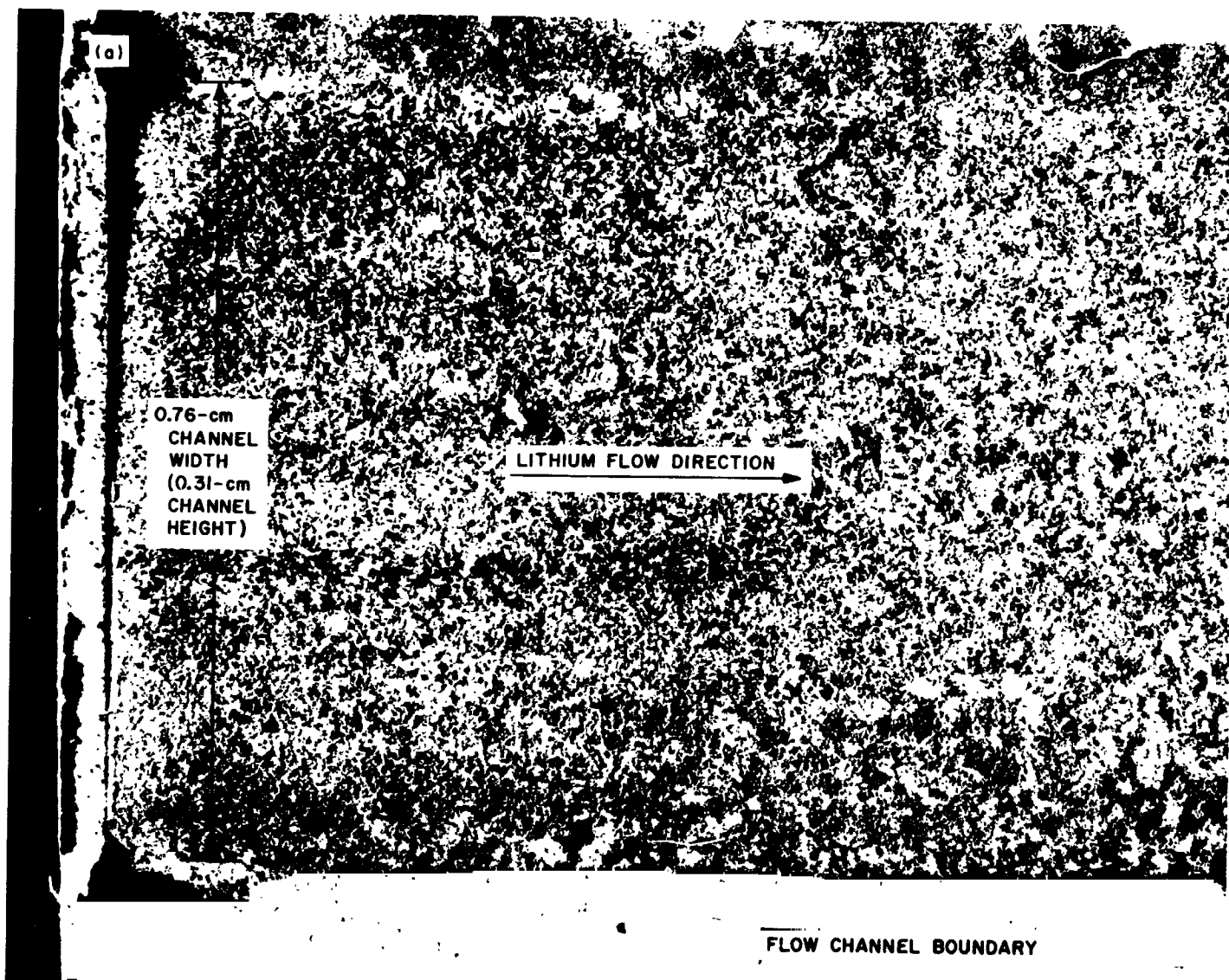


Fig. 11(a). First test specimen after 500 hr at 19.6 m/sec at entrance region

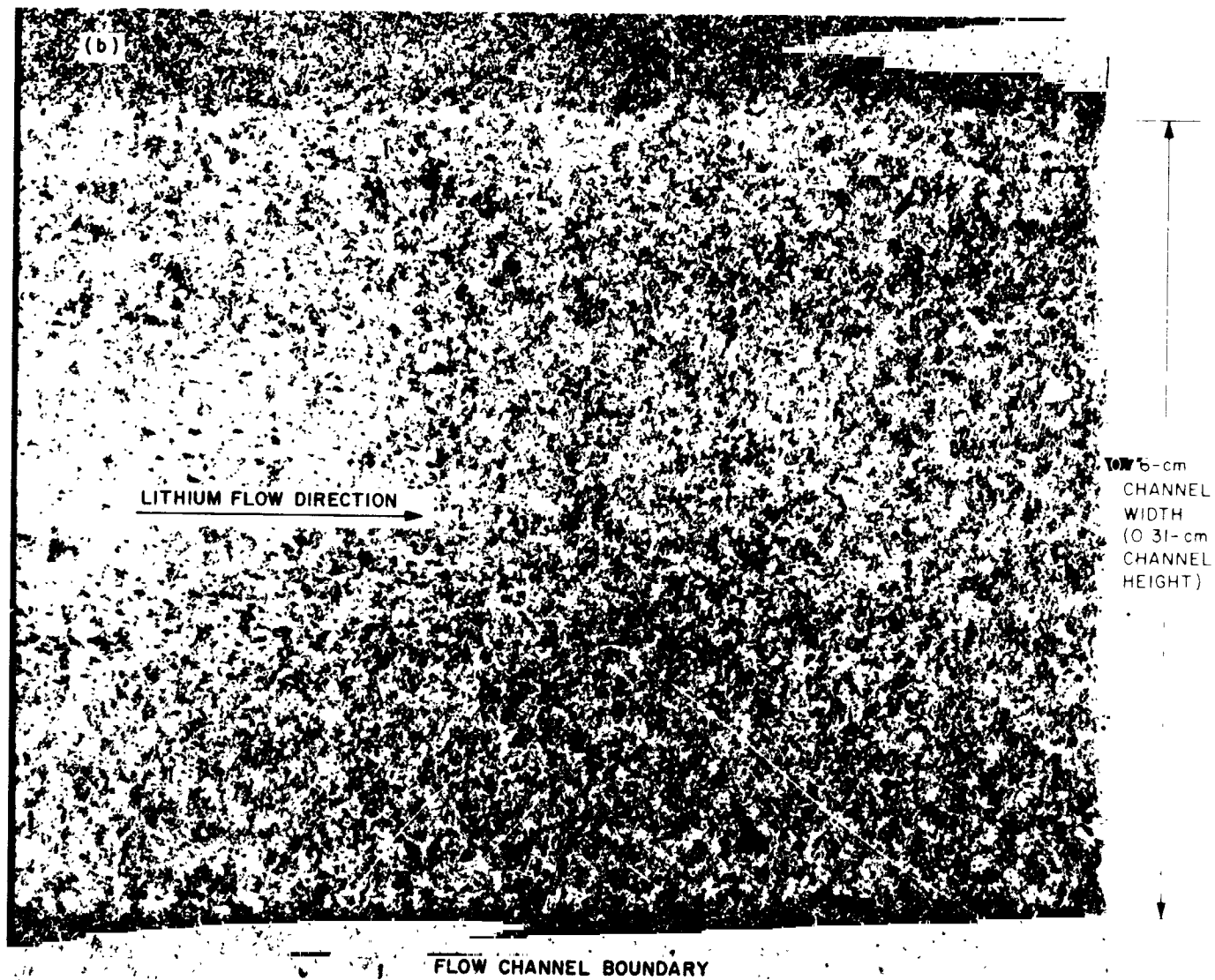


Fig. 11(b). First test specimen after 500 hr at 19.6 m/sec at exit region

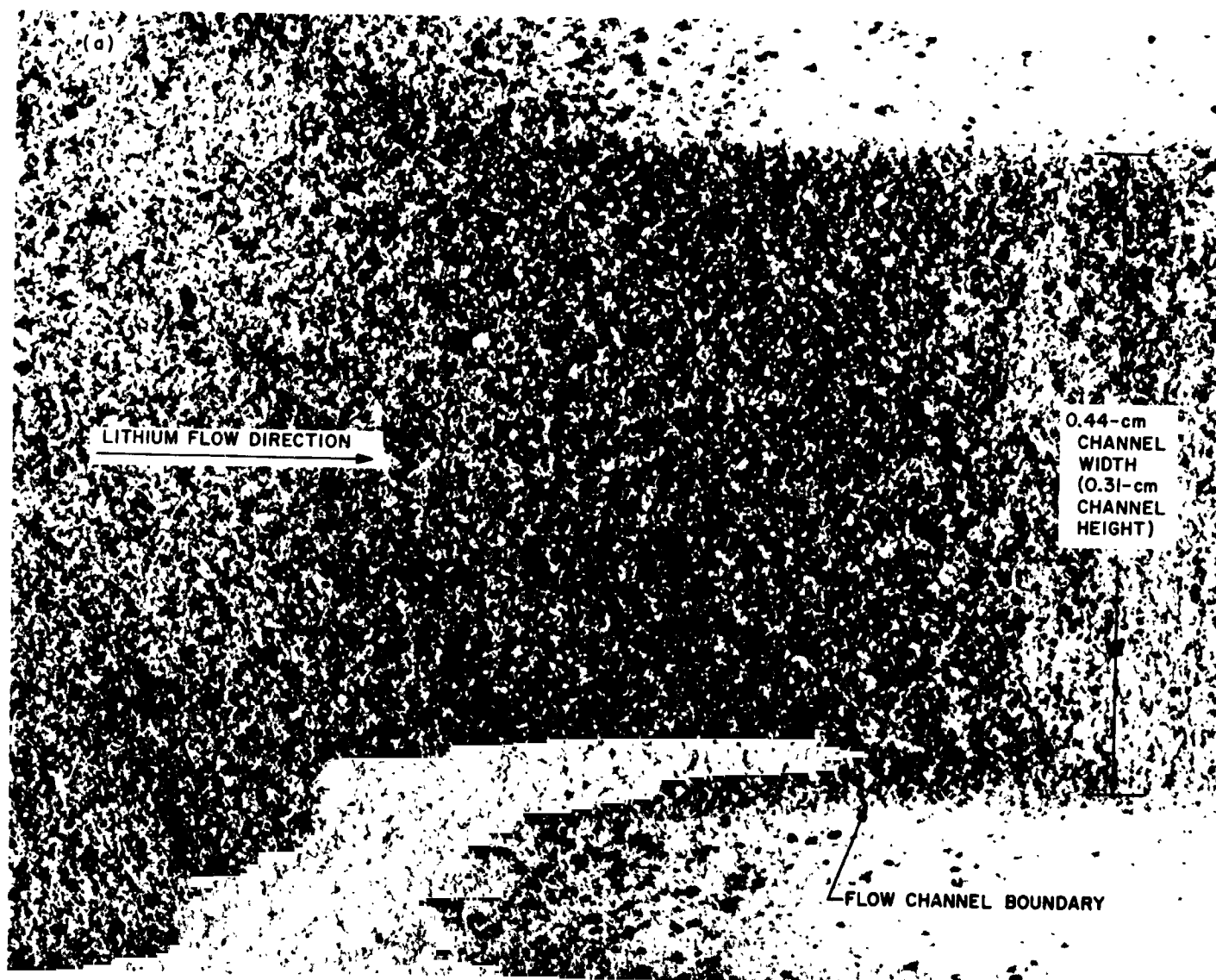


Fig. 12(a). Second test specimen after 500 hr at 33.6 m/sec at entrance region

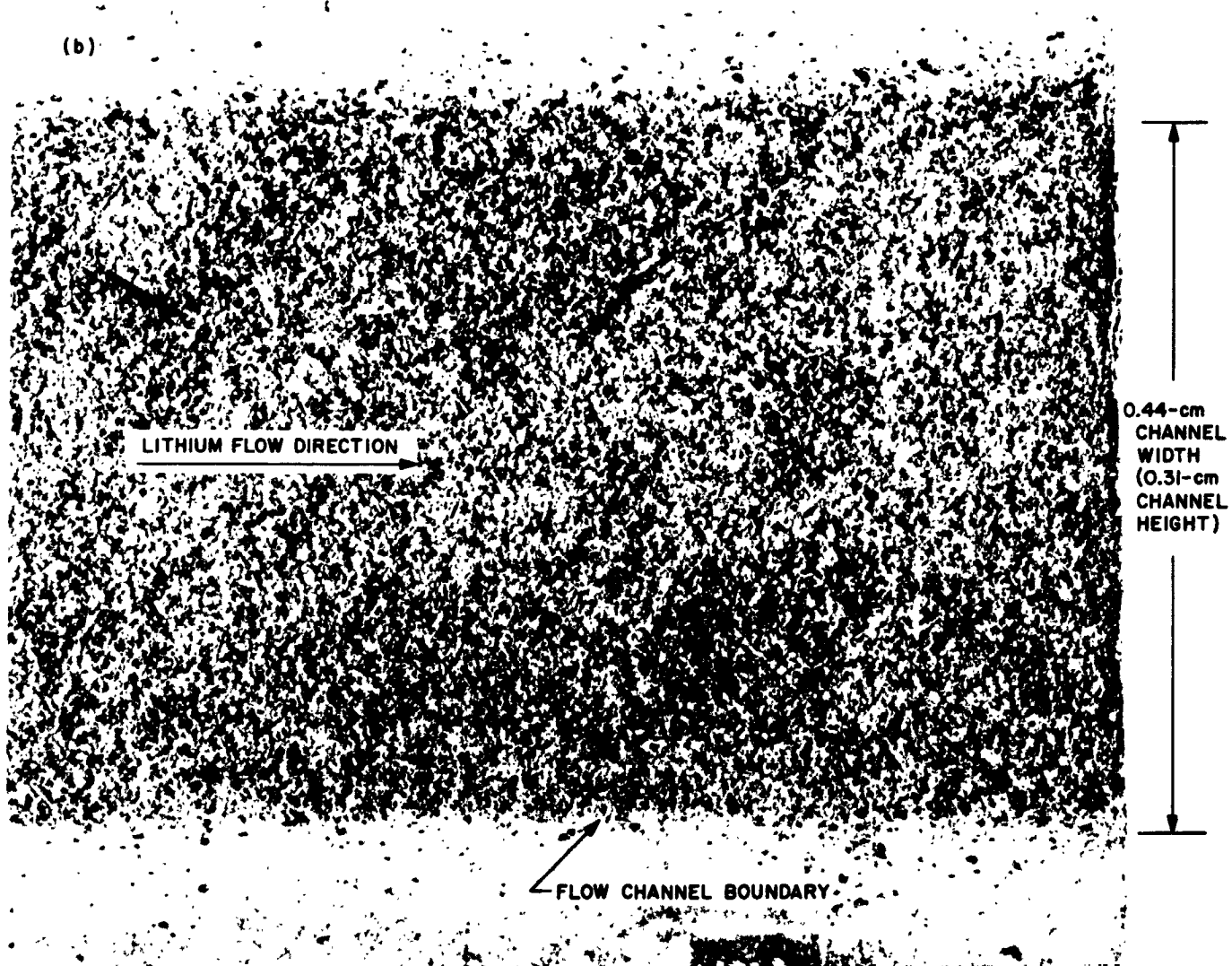


Fig. 12(b). Second test specimen after 500 hr at 33.6 m/sec at exit region



Fig. 13(a). Third test specimen after 500 hr at 48.5 m/sec at entrance region

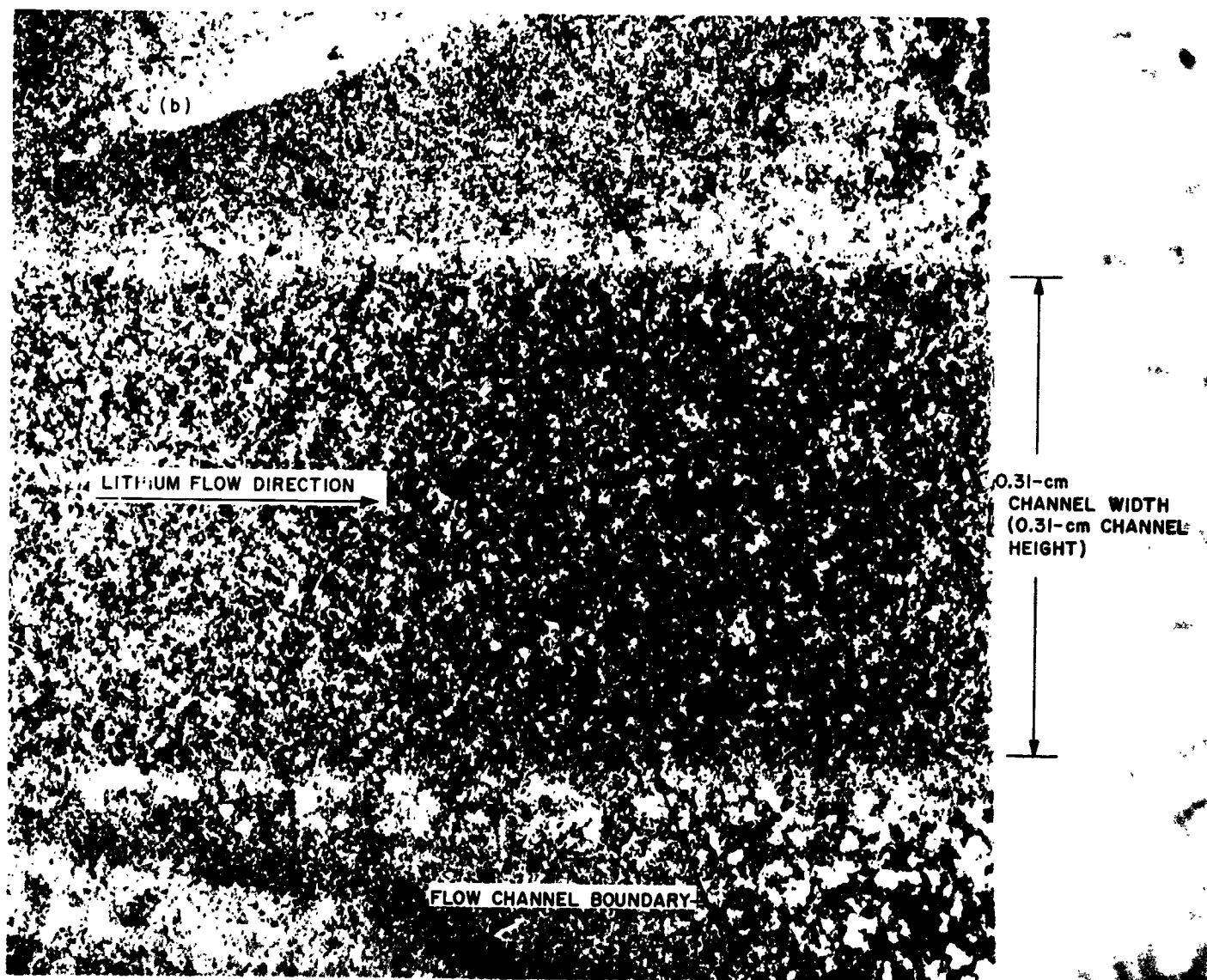


Fig. 13(b). Third test specimen after 500 hr at 48.5 m/sec at exit region

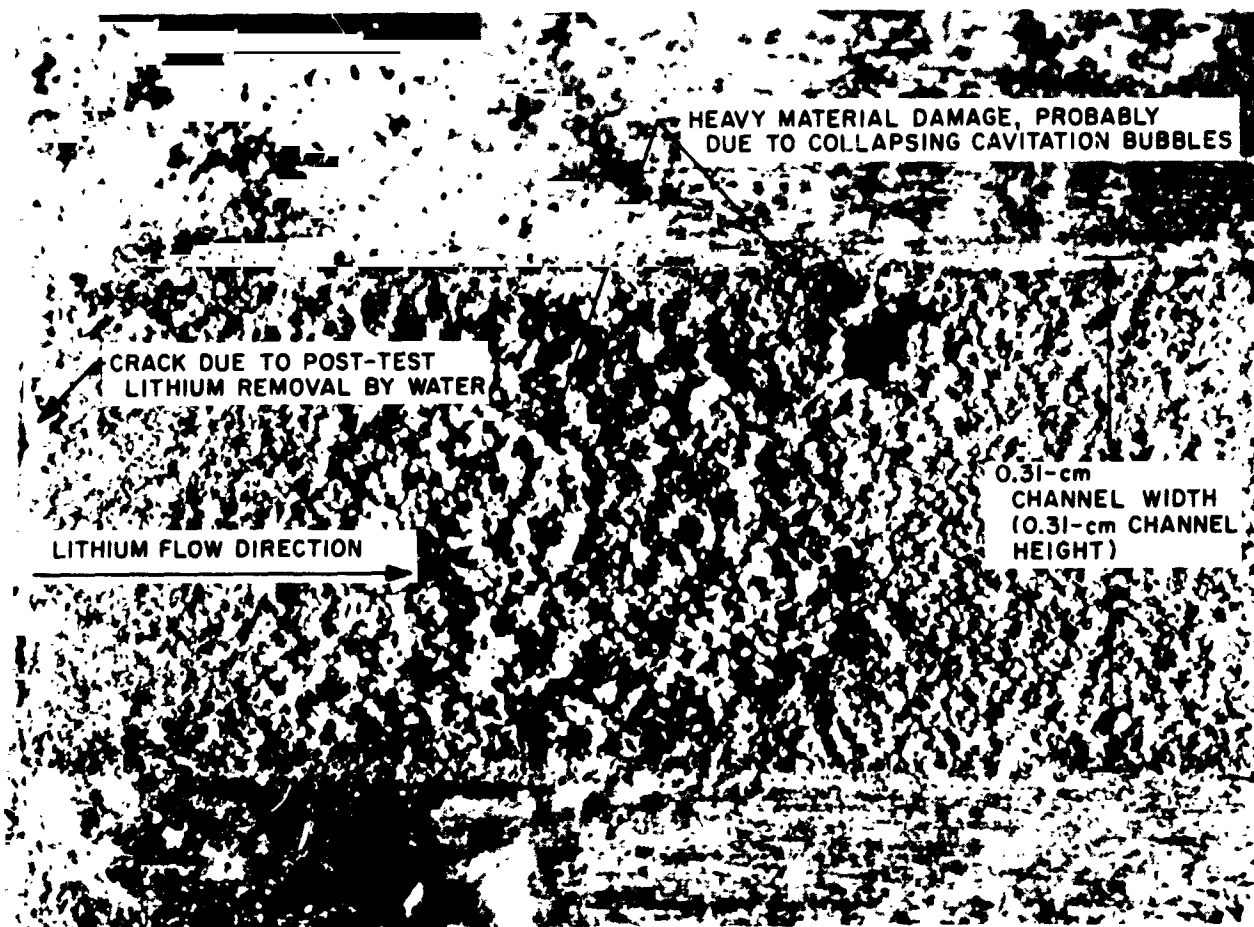


Fig. 14. Flow channel wall downstream of highest velocity step after 500 hr at 48.5 m/sec

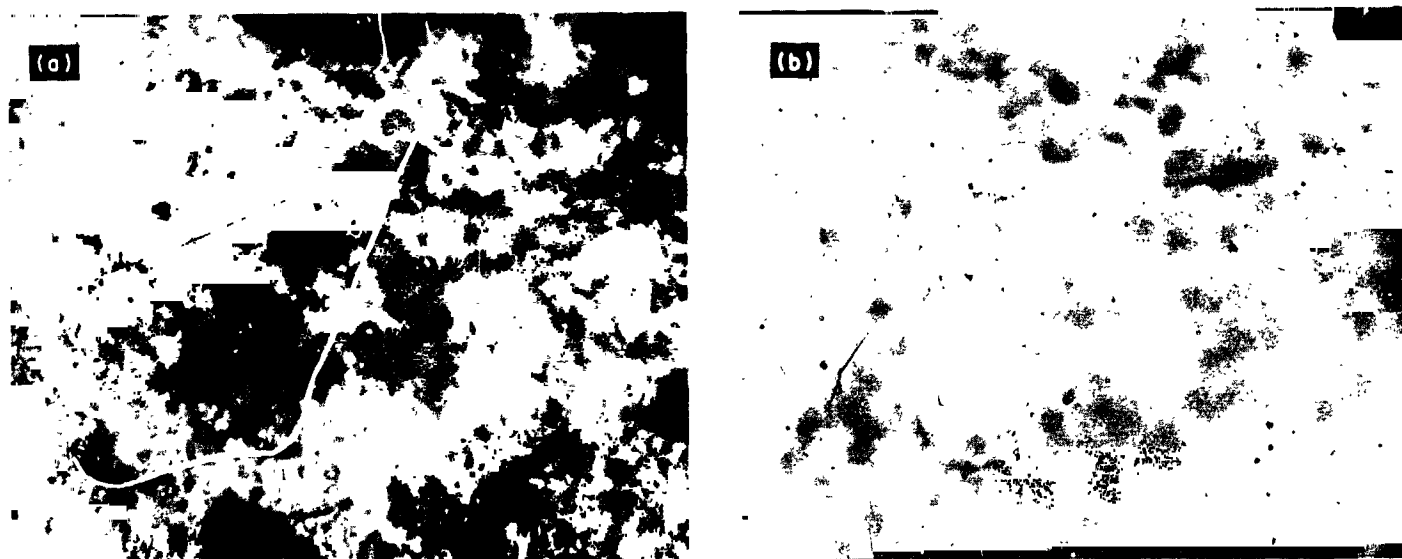


Fig. 15. Test specimen after 500 hr at 48.5 m/sec, $L/d_h = 10$ (250 ×) (a) surface; (b) crystal formation on specimen surface. Largest crystal ~ 54 microns high (Photo reduced to 82%)

Since the lithium was saturated with yttrium at the test temperature, slow cooling of the lithium while maintaining flow resulted in crystal formation on the wall at the high-velocity location. This conclusion is supported by observation that the grooving of the substrate surface, discussed below, was continuous from underneath the crystals to locations where no crystal was formed. A plot of the RMS roughness and average crystal height (measured by a surface profilometer) is shown in Fig. 16 as a function of the peak flow velocity. Both curves have a slope of about 0.8, close to that which would result if turbulent diffusion was the limiting growth mechanism. (The velocity ratios between the specimens remained constant during the cooling down process.)

Measurable material removal, although slight, definitely occurred in the fully developed flow regions. Figs. 15, 17, 18, and 19 are photomicrographs of the surfaces in the

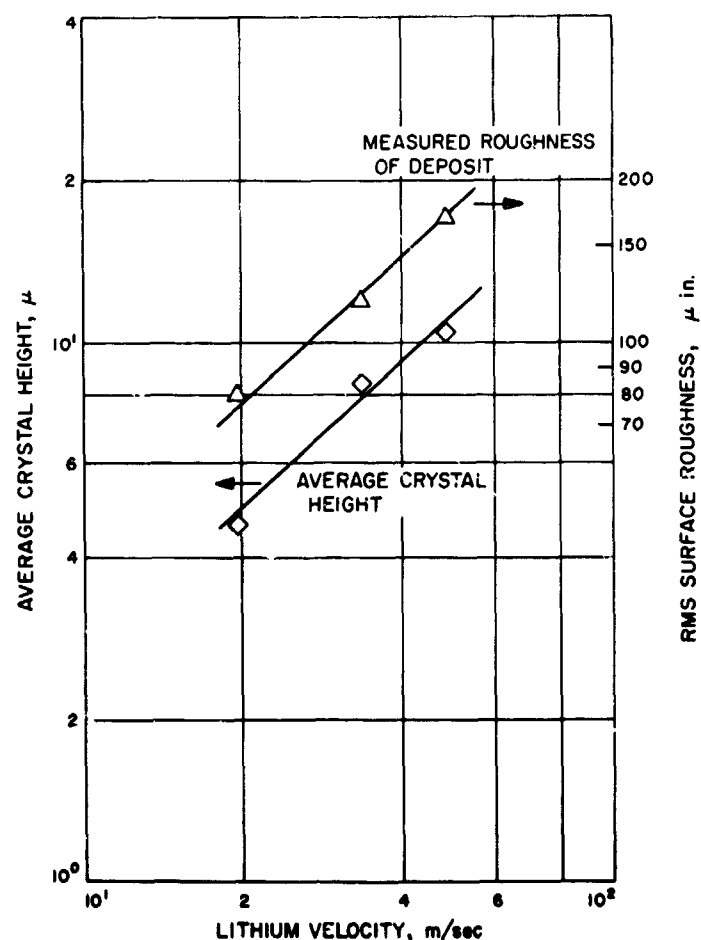


Fig. 16. Roughness and crystal height of yttrium deposit versus lithium velocity



Fig. 17. Test specimen surface in flow channel after 500 hr at 19.6 m/sec (250 ×)
(Photo reduced to 82 %)

flow channel and immediately adjacent to the flow channel (where seepage but little post-test deposition occurred). The most striking characteristic of these photographs is the pronounced grain boundary grooving and the appearance of dislocation pits. The direction of the grooves were completely independent of the direction of flow. The surfaces had no post-test metallurgical preparation, so the grooving and pit formation result from the dissolution of lithium. These surfaces have an appearance typical of over-etched columbium-1% zirconium specimens. A 750 × photomicrograph of the grooving is shown in Fig. 20.

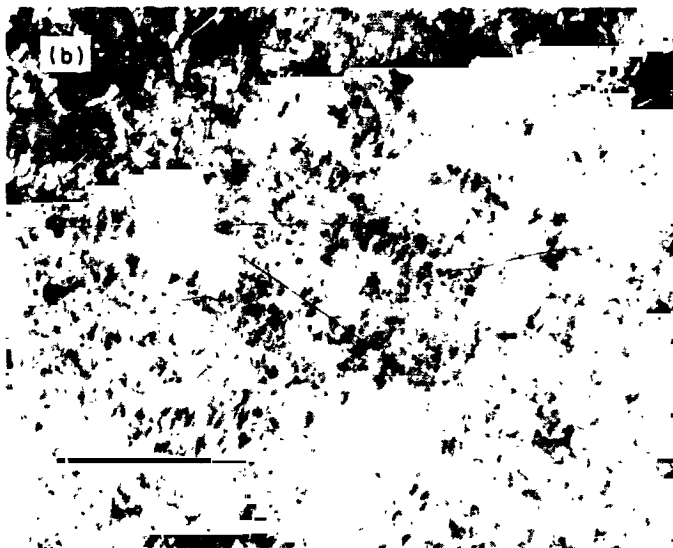
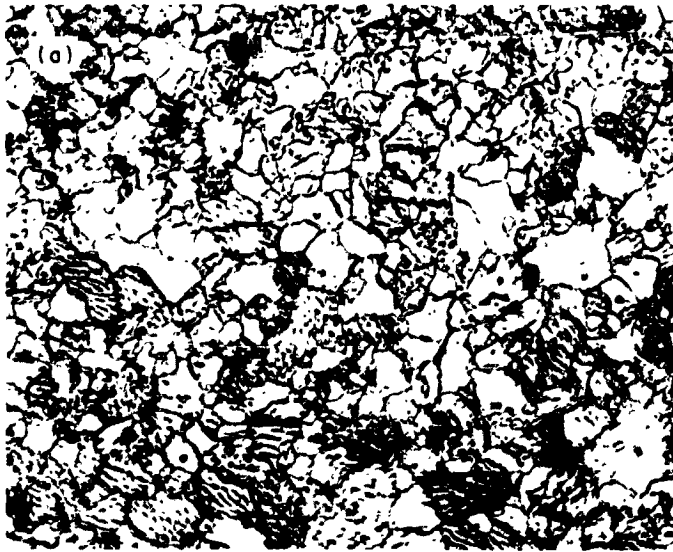


Fig. 18. Test specimen surfaces of 33.6-m/sec flow channel after 500 hr (250 $\times$): (a) adjacent to flow channel; (b) in flow channel (Photo reduced to 82%)

Traverses of the surfaces at $L/d_h = 10$ were made with a microscope with a calibrated vernier focusing mechanism. Divisions on the scale were in 2-micron increments, and repeatability was within about $\frac{1}{2}$ micron with the approach from a consistent direction. The results of measurements on the Cb-1%Zr are shown in Fig. 21 for the three different regions of flow velocity. The arrows define the limits of the flow region.

4. Comparison with Predicted Values

Two extremes of material loss were estimated as illustrated in Fig. 21. One method was measurement of the

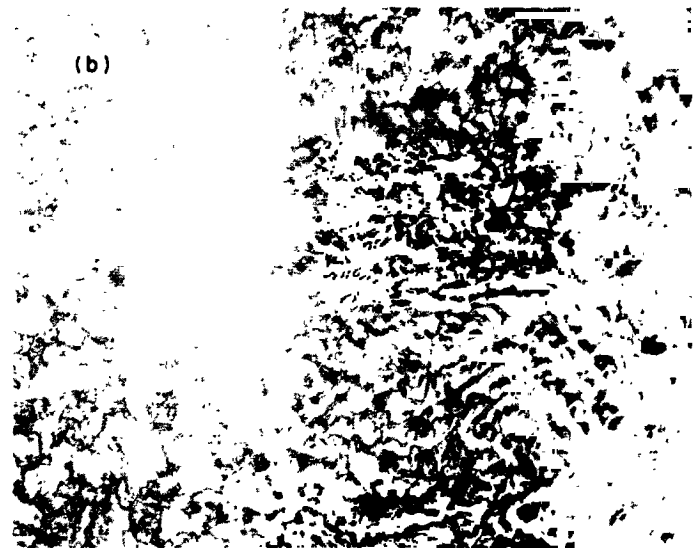
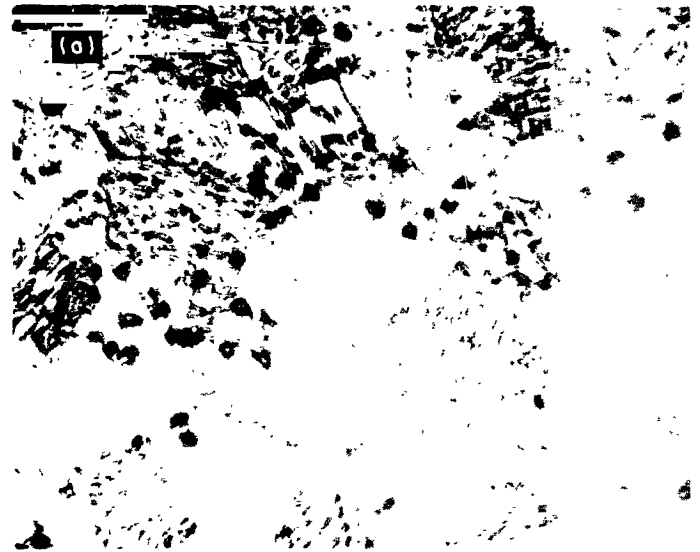


Fig. 19. Test specimen surfaces of 48.5 m/sec flow channel after 500 hr (250 $\times$): (a) adjacent to flow channel; (b) at boundary of flow channel (Photo reduced to 82%)

distance between the peak-to-peak tangent and the lowest valley in the flow channel. The other method was to fair a line through the surfaces outside of the flow region and measure the maximum valley depth below that line. The results of these measurements are plotted on Fig. 22 as a function of velocity. The calculated curve is shown for comparison. The most important finding is that the highest velocity test specimen exhibited a maximum material loss rate of about one-eighth of the predicted value. At 48.5 msec (159 ft/sec) the predicted value is 66.7 microns ($\sim 2\frac{1}{2}$ mil) while the measured estimates range from 5.5 to 8.5 microns. This factor of eight is actually



Fig. 20. Cb-1%Zr dislocation grooving due to lithium dissolution. Test specimen surface adjacent to 48.5-m/sec flow channel (750 X)
(Photo reduced to 82%)

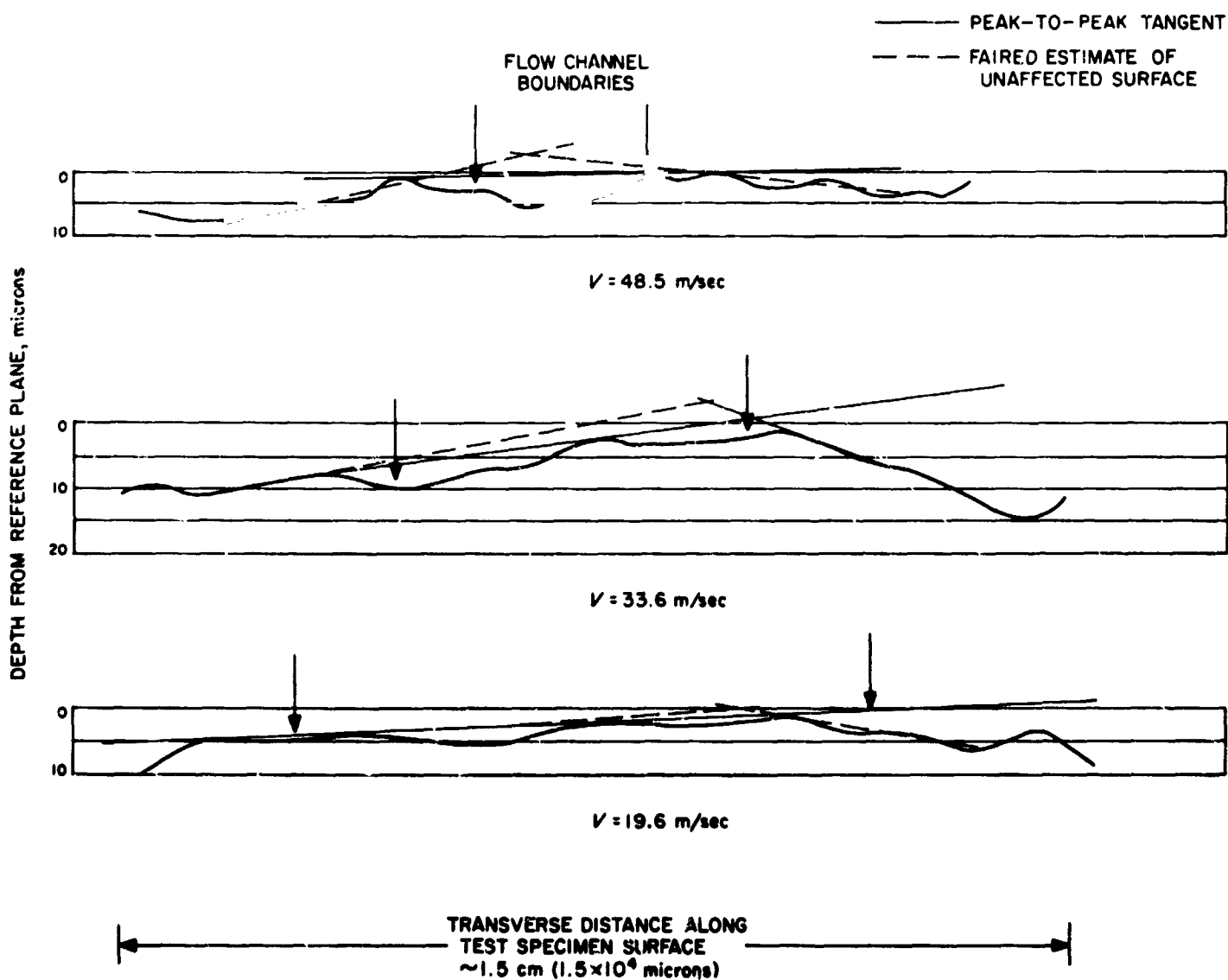


Fig. 21. Test section traverses $L/d_h = 10$

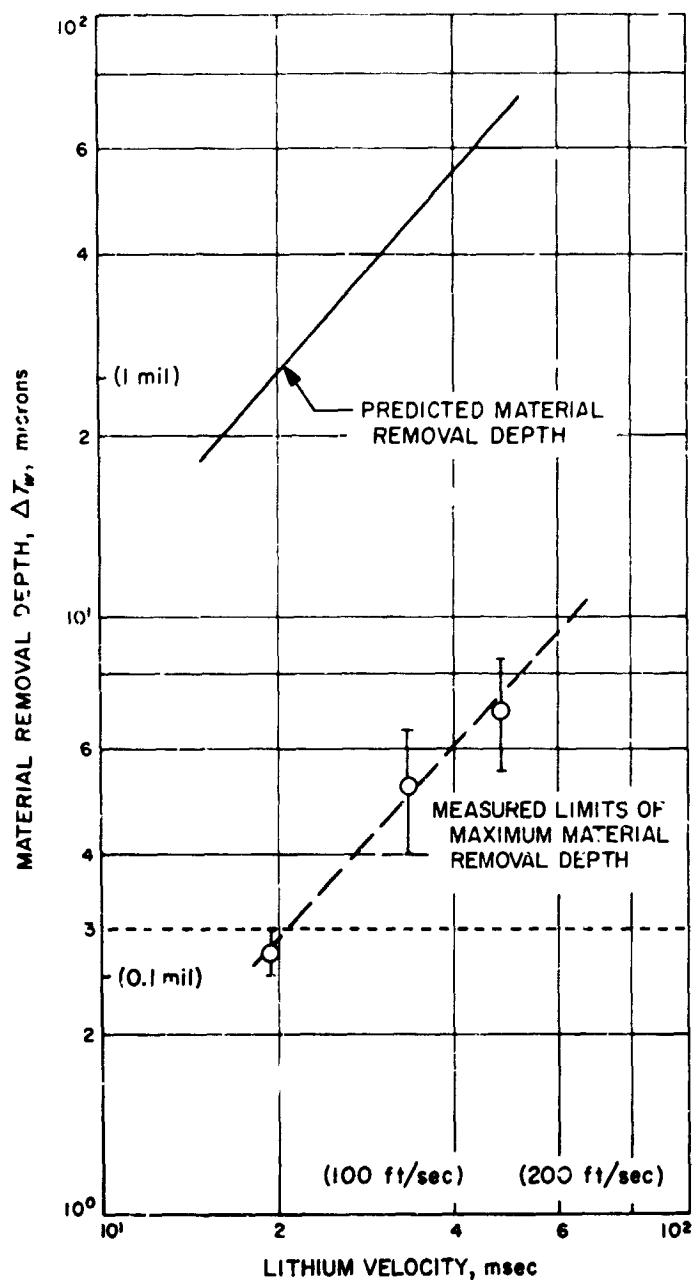


Fig. 22. Comparison of measured and predicted material removal depth versus lithium velocity. 500 hr at 1088°C average lithium temperature, differential temperature $\approx 7.5^\circ\text{C}$

well within the uncertainty of the existing solubility data (a factor of greater than 10 scatter) and the diffusivity calculation (a factor of 2 uncertainty). The slope of the test data is reasonably close to the slope of the predicted values (≈ 0.9) which result from a diffusion-limited process. Therefore, turbulent mass-transfer relations based on simple dissolution may be adequate for conservative estimates of mass transfer in columbium-lithium systems.

For the range 1070 to 1150°C, if the equation for diffusivity is taken as valid, a preliminary empirical relation for mass transfer based on the maxima of the test data is

$$\Delta t_w = 6 \times 10^{-10} k_d \frac{\rho_s}{\rho_w} \tau (T_w - T_c) \quad (10)$$

where k_d is given by Eq. (1).

Further refinement of these calculations, and chemical and metallurgical analyses of the other test loop components, are continuing. When complete, it is anticipated that the constant in Eq. (10) may change by a significant amount due to changes in T_c . In any event these tests have demonstrated that there is no unusual or unexpected corrosion effect resulting from high velocities, and the material loss is significantly less than would be predicted based on the mean values of existing solubility data.

Application of Eq. (1) will be illustrated by consideration of the 10,000-hr operation of a liquid MHD system with a maximum velocity of 150 m/sec (500 ft/sec). The maximum possible temperature difference in the high-velocity region would be on the order of 5°C . Since the flow rate would be approximately 80 kg/sec (130 lb/sec), this temperature difference represents a heat loss and kinetic losses of 1200 kw from the lithium stream, the most likely to be encountered. For this example, the hydraulic diameter at the high-velocity location is 0.38 cm, giving a channel Reynolds number of 1.7×10^6 . The Sherwood number is therefore 4.4×10^3 , and the mass transfer coefficient $k_d = 4.8 \text{ cm/sec}$.

Substitution in Eq. (10) gives $\Delta t_w = 0.027 \text{ cm}$ (0.011 in.). This loss (or deposit thickness) is within acceptable limits, since the wall thickness and minimum channel opening are several times as great. Further studies have been initiated to more accurately determine the temperature and velocity history of the lithium in a 300-kwe liquid MHD system. It is probable that the effective temperature difference will be much less than 5°C , giving a correspondingly smaller mass transfer value.

C. Lithium-Boiling Potassium Test Loop

Operations, Phase II, G. M. Kikin, W. M. Phillips, and M. L. Peelgren

1. Test Loop Operations: November 1966 to January 1967

The period between the end of Phase I and Phase II operations (June to November 1966) was devoted to field

installations and TIG welding into the loop of a new preheater, instrumentation changes, and repairs, addition of three Bourdon gauges to the potassium loop; changes and additions of loop trace heaters and radiator-condenser (R-C) heaters; repairs to valves and manipulators, installation of a screen to stop particulate matter from entering the argon-air heat exchanger; rerouting piping to eliminate argon flow through the radiator-condenser chamber; remagnetization of flowmeter magnets to bring flux back to full strength; repairs to the lithium heater, potassium preheater, and potassium pump power supplies; installation of a backup Dowtherm pump and motor, replacement of catalytic units in the argon purifier; repairs to the lithium pump power supply; and installation of an automatic argon makeup system to maintain tank argon pressure at the desired preset pressure level of about 5 psig.

Initial startup operations included outgassing the tank walls and the loop at 400 to 500°F and flushing the secondary loop with a full charge of potassium. After dumping the flushing charge, the secondary loop was "hard-filled" again with a fresh charge of potassium.

Several smooth starts and stops were made on the lithium pump to ascertain satisfactory pump operation. Heat losses from the boiler, preheater, and lithium heater were next determined under no-flow conditions. These losses were obtained by applying power to the trace heaters on the boiler and directly to the potassium preheater and lithium heater, so as to maintain these components at preselected temperatures. Under steady-state conditions, the power input equals the heat losses at a zero-flow condition. These heat loss tests were run at temperatures from 400 to 1200°F, and the results are plotted in Fig. 23.

Calibration of the potassium and lithium flowmeters was accomplished by comparing the flowmeter signals against the actual potassium and lithium flowrates. These flowrates were calorimetrically determined by measuring the rise in fluid temperature across the lithium heater and the potassium preheater for given power inputs. The calibration factors obtained are: $F_K = 200$ lb potassium/hr-mv and $F_{Li} = 134$ lb lithium/hr-mv.

With the secondary loop completely full of liquid potassium, tests were performed to determine the over-all average heat-transfer coefficient in the boiler for liquid-liquid operation. Variation of the potassium flowrate while maintaining the lithium flow constant will permit determination of the liquid lithium heat transfer

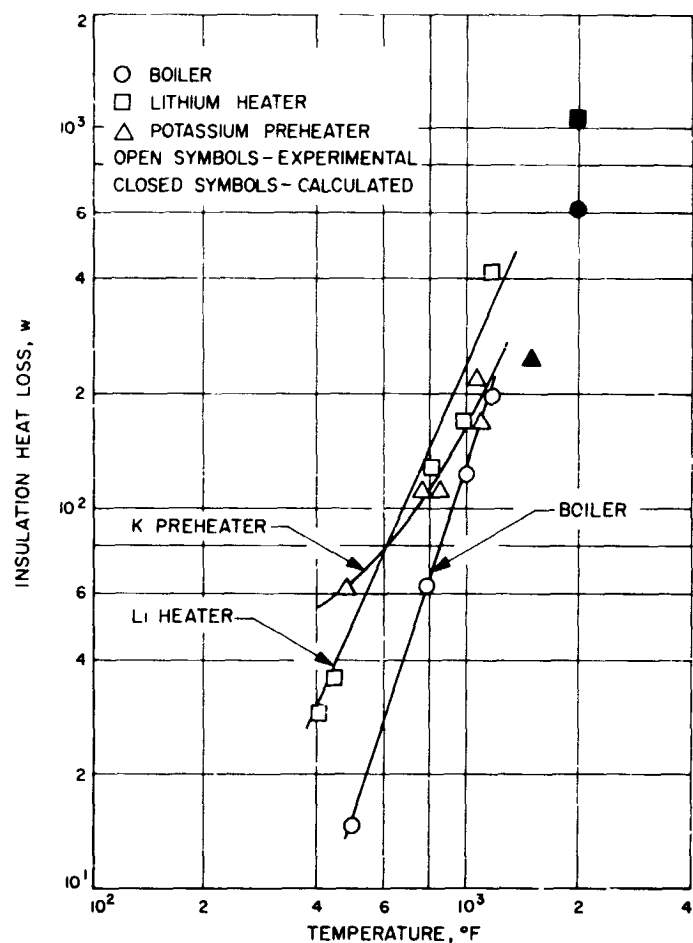


Fig. 23. Lithium heater, potassium preheater, boiler heat losses

coefficient using the "Wilson plot" technique, which is a graphical technique of interpreting heat-transfer coefficients in heat exchange.

Preliminary analysis of liquid-liquid heat-transfer test data indicates the over-all liquid-liquid boiler heat transfer coefficients to be ~ 1500 to 1650 Btu/hr-ft²-°F. This compares very well with the calculated value of U_o (over-all heat transfer coefficient) of 1630 Btu/hr-ft²-°F using the Lubarsky-Kaufman equation for liquid metal heat transfer in annuli.

Following calibration of the flowmeters, the lithium pump flowrate was then determined as a function of the pump speed. This calibration is shown in Fig. 24. The actual flowrate, at the nominal design pump speed of 3500 rpm, is ~ 1000 lb/hr, which is about 17% less than the design flowrate of 1200 lb/hr. During operations the pump was usually operated at ~ 2100 rpm, as previous high-speed operation had resulted in pump seizure. At this lower pump speed the flowrate is ~ 800

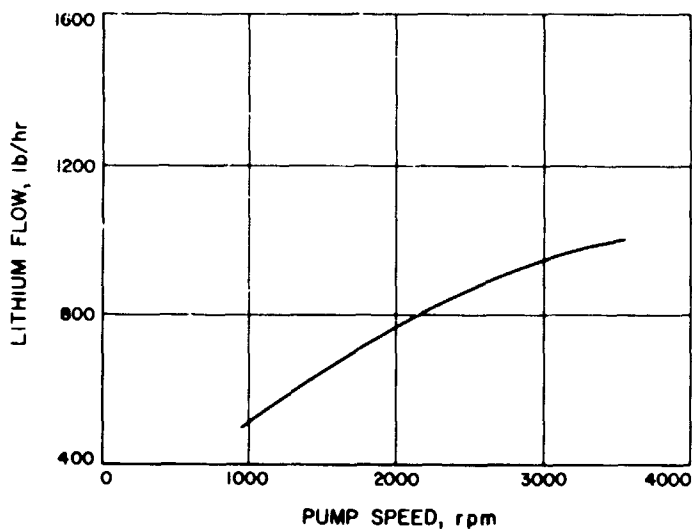


Fig. 24. Lithium flowrate versus pump speed

lb/hr which proved to be satisfactory, as the primary fluid flowrate is not a critical parameter in tests on this two-fluid experimental loop.

After the liquid-liquid tests were completed, boiling was initiated by draining about one-half the potassium out of the secondary loop into the potassium dump tank. Draining the loop of this quantity of potassium produces a liquid level in the radiator-condenser of about half its height. The potassium drain was accomplished in about five individual draining steps wherein a small amount of potassium was drained each time and then the drain valve closed in order to establish loop equilibrium conditions before the next potassium drain. The boiling startup oscillations which started at the time of potassium drain are shown in Fig. 25, which is a Sanborn 8-channel pen-recording showing the following loop

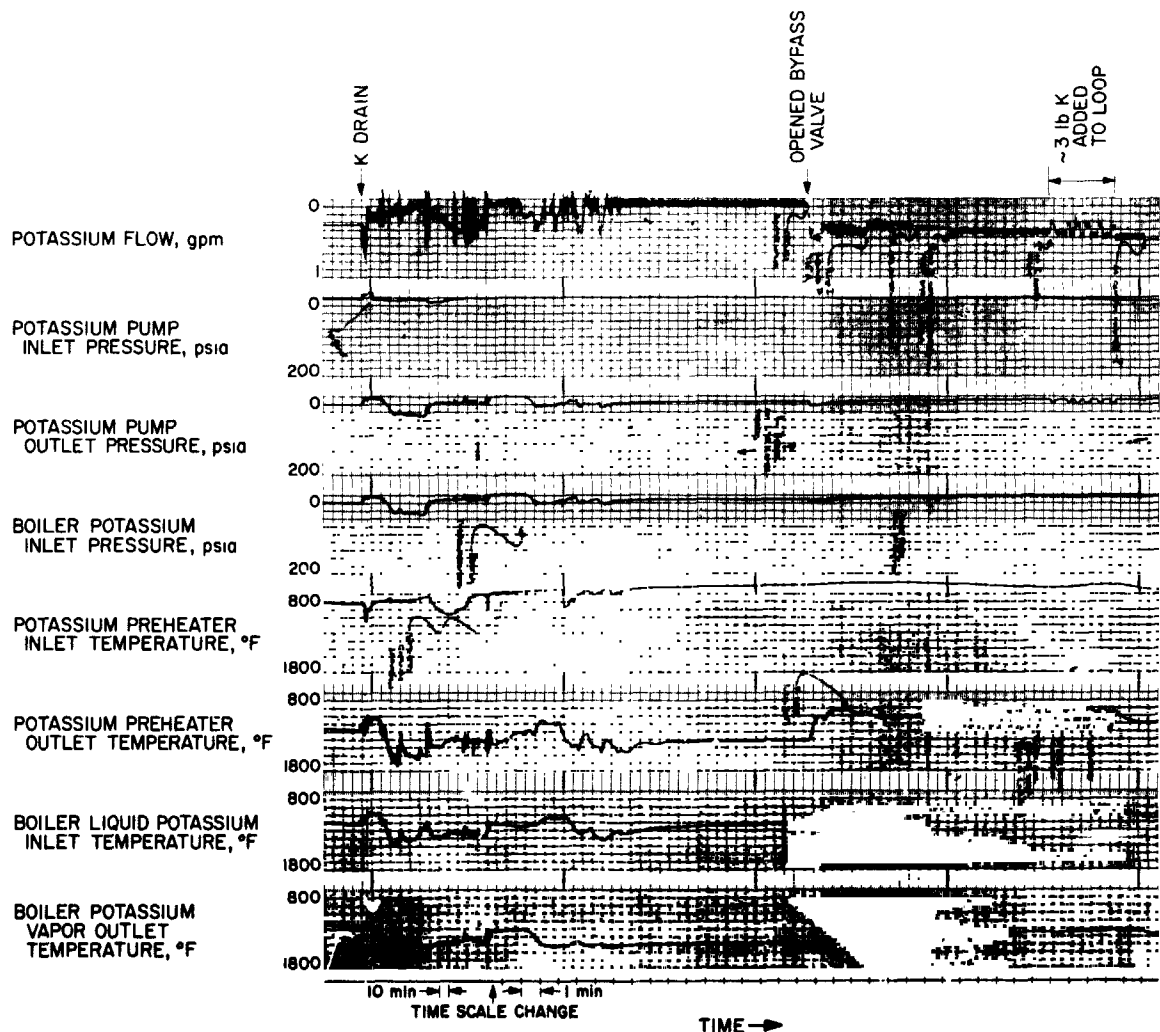


Fig. 25. Sanborn multichannel trace during boiling startup

parameters: potassium flowrate, potassium pump inlet pressure, potassium pump outlet pressure, potassium boiler inlet pressure, potassium preheater inlet temperature, potassium preheater outlet temperature, liquid potassium boiler inlet temperature, and potassium vapor outlet temperature.

Flow oscillations occurred after the turboalternator-bypass valve was closed. These oscillations eventually were damped out and fairly steady boiling occurred, but at a very low potassium flowrate of about 0.07 gpm. The flow oscillations were about ± 0.03 gpm. Opening the bypass valve increased the potassium flow to about 0.4 gpm. However, the flow oscillations increased to about 0.1 gpm (peak-to-peak). Increasing the potassium pump current from 750 to 1000 amp reduced the flow oscillations to about 40% of its former value. In order to determine if even these remaining flow oscillations were due to potassium pump cavitation, potassium was added to the loop from the dump tank, and the potassium level was brought up to two-thirds the height of the radiator-condenser. This potassium addition, plus concurrent heating (using radiator-condenser heaters) of the potassium condensate (thus raising the potassium pump

inlet pressure) resulted in an extremely steady liquid potassium flow. Steady-state boiling at high temperatures (1700 to 1900°F) and high powers (20 to 30 kw) were readily achieved. For this lithium-boiling potassium system, at least, satisfactory nominal operating condition stability can be achieved without resorting to feedback control. Fig. 26 is a typical Sanborn strip chart recording during steady-state boiling operations.

In order to determine the nature of the small potassium flow and pressure oscillations during smooth steady-state boiling, the flow and pressure signals to the Sanborn recorder were amplified $10\times$, and the chart speed was increased to its maximum of 100 mm/sec. Fig. 27 shows the resulting recording. The oscillations of shortest duration are those due to 60 cycle "noise" superimposed on the flowmeter and the thermocouple signals due to instrumentation noise or 60-cycle noise from the loop itself. It can be seen that the peak-to-peak fluctuation of the liquid potassium flowrate was only 0.01 gpm or only about $\pm 1\%$ of the nominal flow (0.45 gpm).

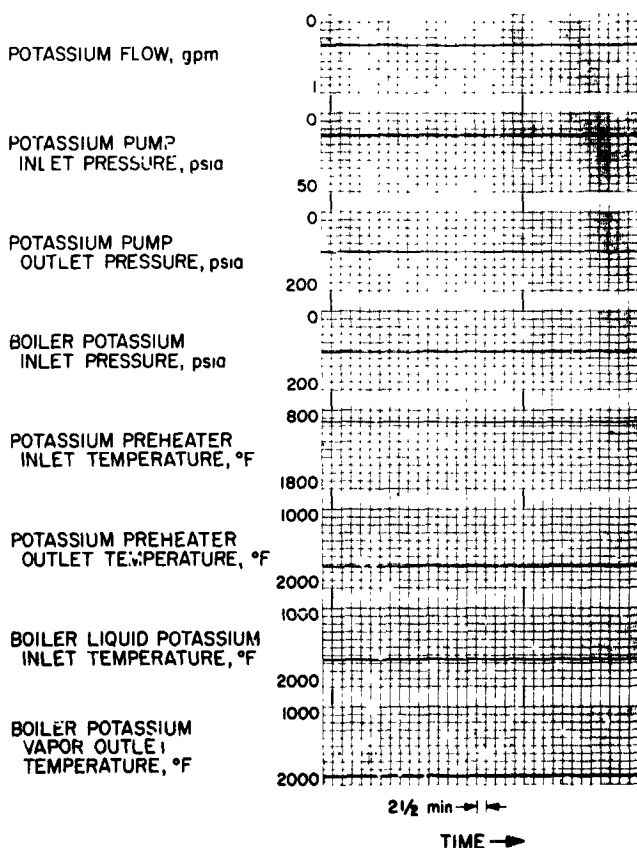


Fig. 26. Sanborn strip-chart trace: steady-state boiling

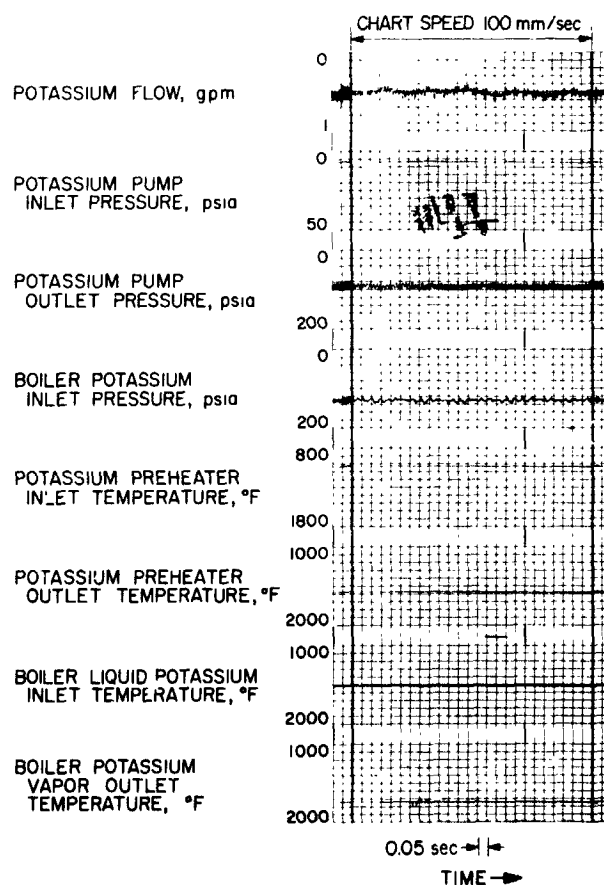


Fig. 27. Sanborn strip chart: steady-state boiling (high-speed and amplified signal)

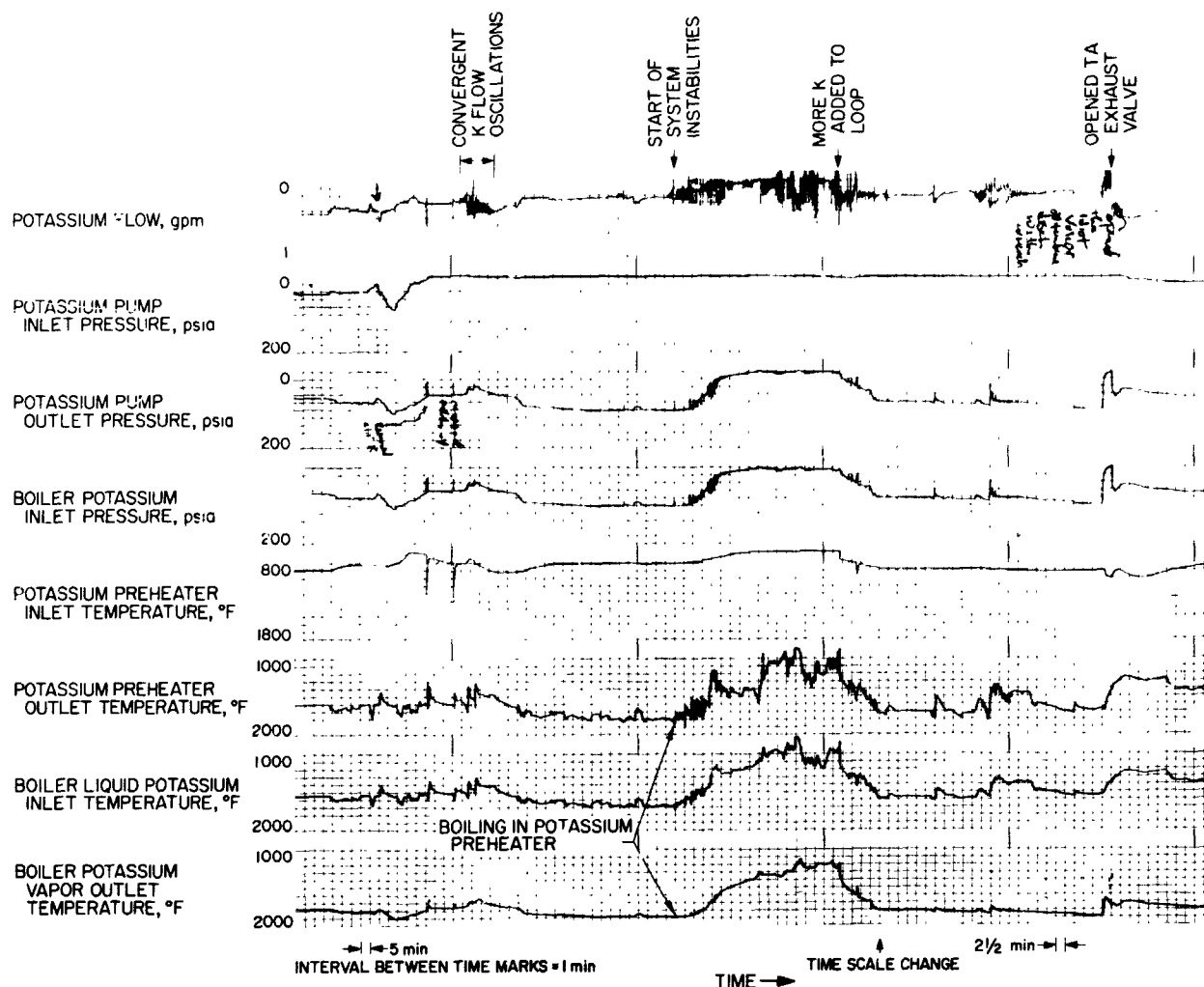


Fig. 28. Sanborn strip-chart recording of system instabilities

Erratic behavior was experienced when all the potassium vapor flow was directed to the turboalternator (T-A), but with the T-A exhaust valve only partially open. This flow restriction at the exhaust valve caused the T-A to back-fill with liquid potassium, causing periodic voiding of the liquid potassium condensate volume in the R-C, since the T-A internal volume is about equivalent to the potassium condensate volume in the R-C.¹ This caused pump cavitation which subsequently would result in flow oscillations and system instability (Fig. 28). Periodically

¹The potassium liquid vapor interface in the radiator condenser is determined by taking a trace of the individual radiator-condenser coil temperatures at any one time. In the condensing region in the top of the coil the temperature will be essentially constant, but will drop rapidly in the lower portion of the R-C which contains the potassium condensate. A typical R-C temperature trace showing the vapor liquid interface is shown in Fig. 29.

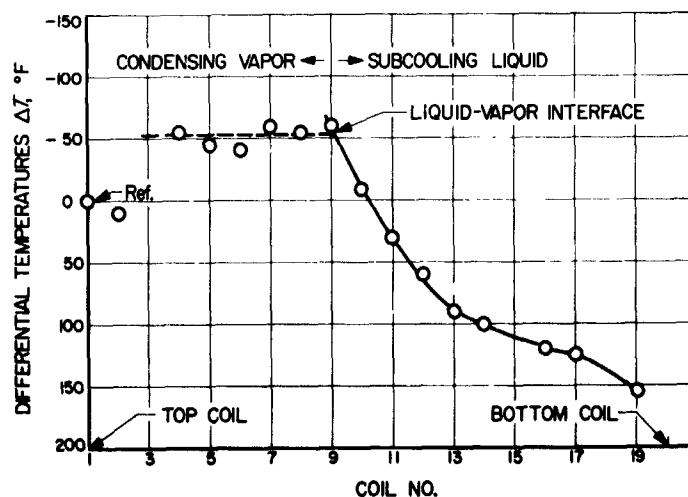
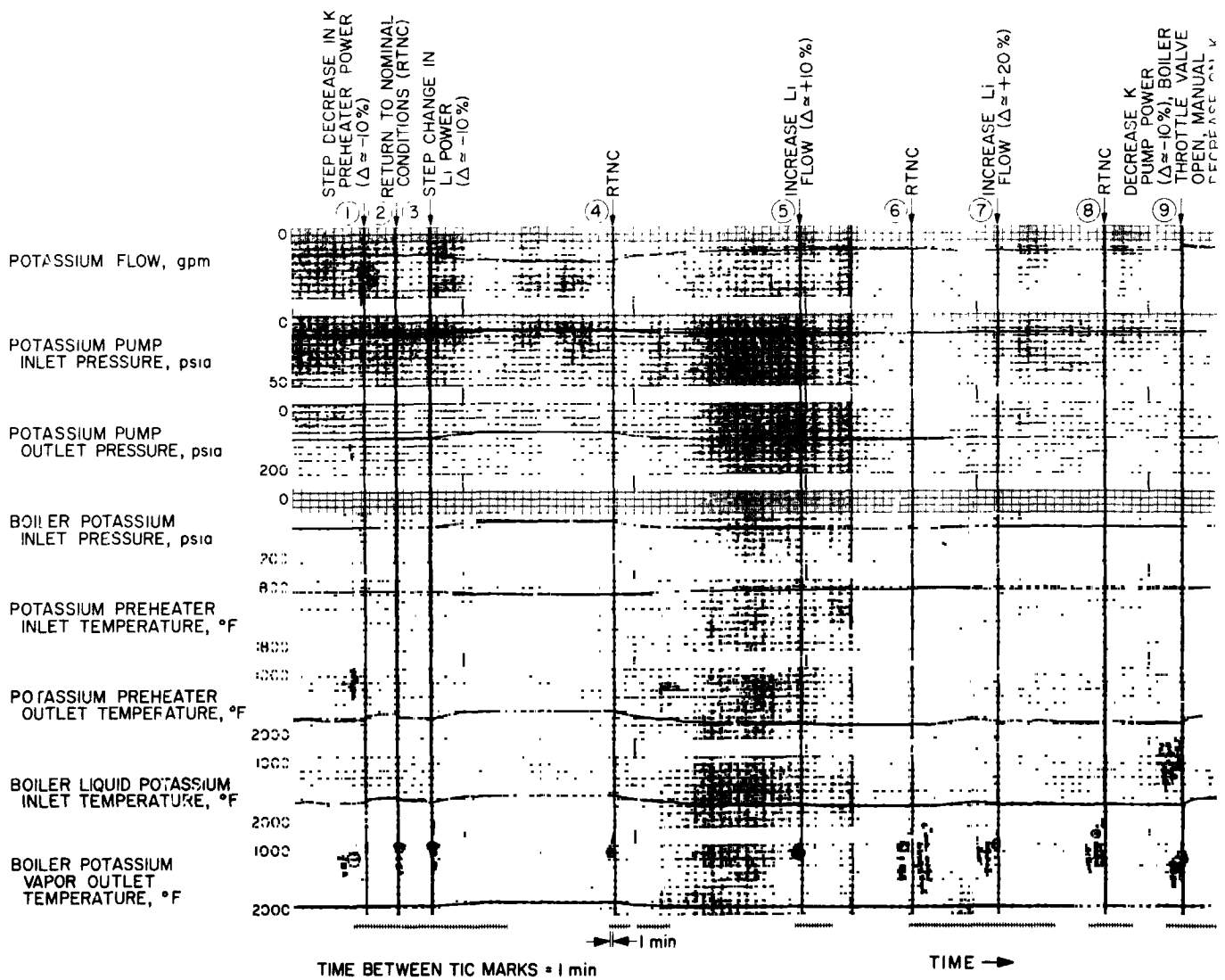


Fig. 29. Plot of radiator-condenser temperature versus axial-coil height



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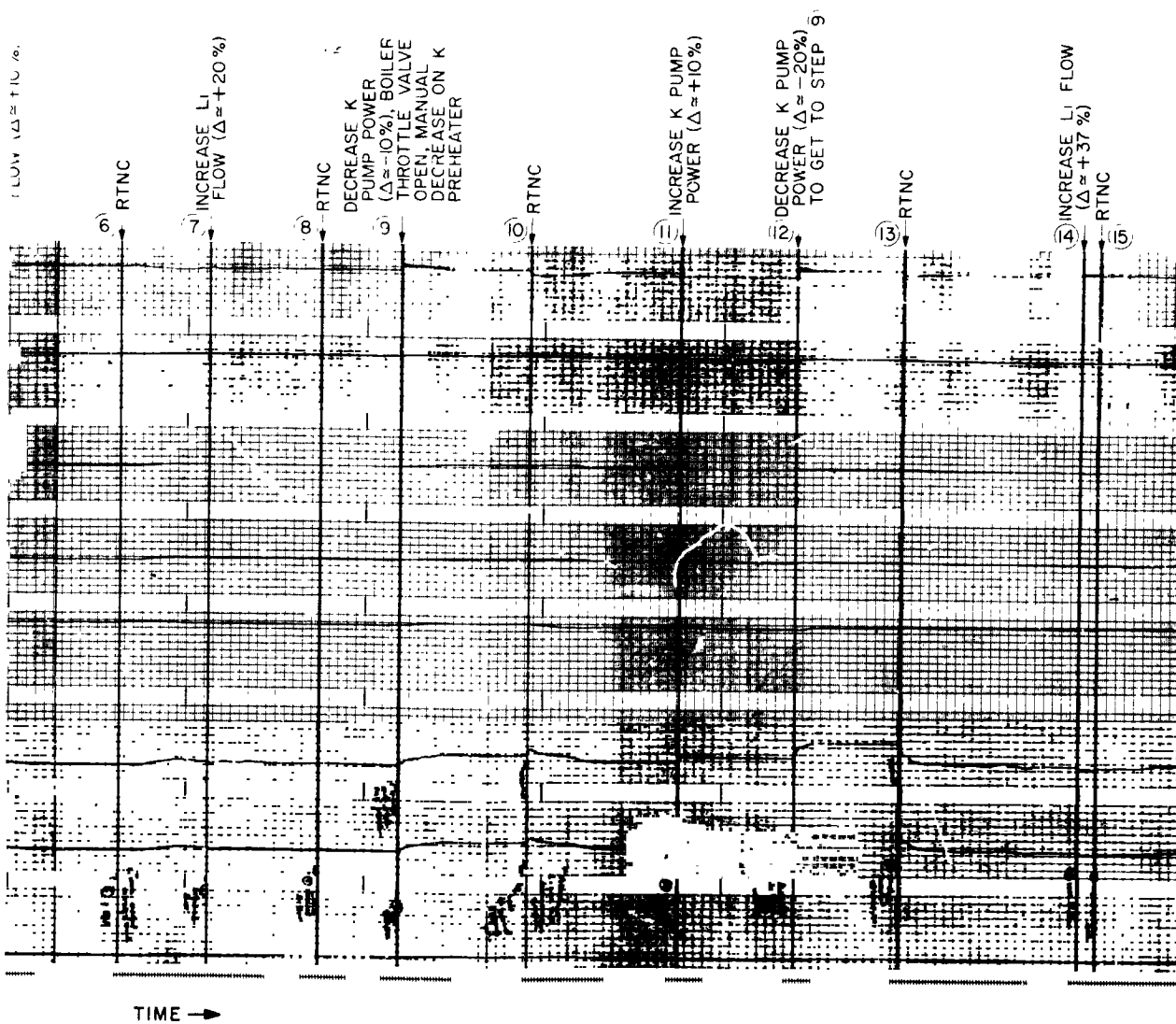


Fig. 30. Sanborn strip-chart recordings: transient tests 1-15

the liquid potassium in the T-A would drain back into the R-C with reestablishment of stable operation. This sequence of events leading to erratic loop behavior was relieved by further opening the T-A exhaust valve; nominal potassium flow then ensued, and system stability was excellent.

A series of tests were performed to determine transient system behavior for various perturbations. The various perturbations (all of which were essentially step changes) fall under the following major classification:

- (1) Step changes in potassium preheater power
- (2) Step changes in lithium heater power
- (3) Step changes in lithium flow

- (4) Step changes in potassium flow
 - (a) Boiler throttle valve fully open
 - (b) Boiler throttle valve partially closed
- (5) System scram—lithium power shutoff

The Sanborn chart recordings of the transient tests (Nos. 1 to 22) are shown in Figs. 30, 31, and 32.

The descriptive title of each of these transient tests are as follows:

- (1) Step decrease in potassium preheater power ($\Delta \simeq -10\%$)
- (2) Return to nominal conditions
- (3) Step change in lithium power ($\Delta \simeq -10\%$)

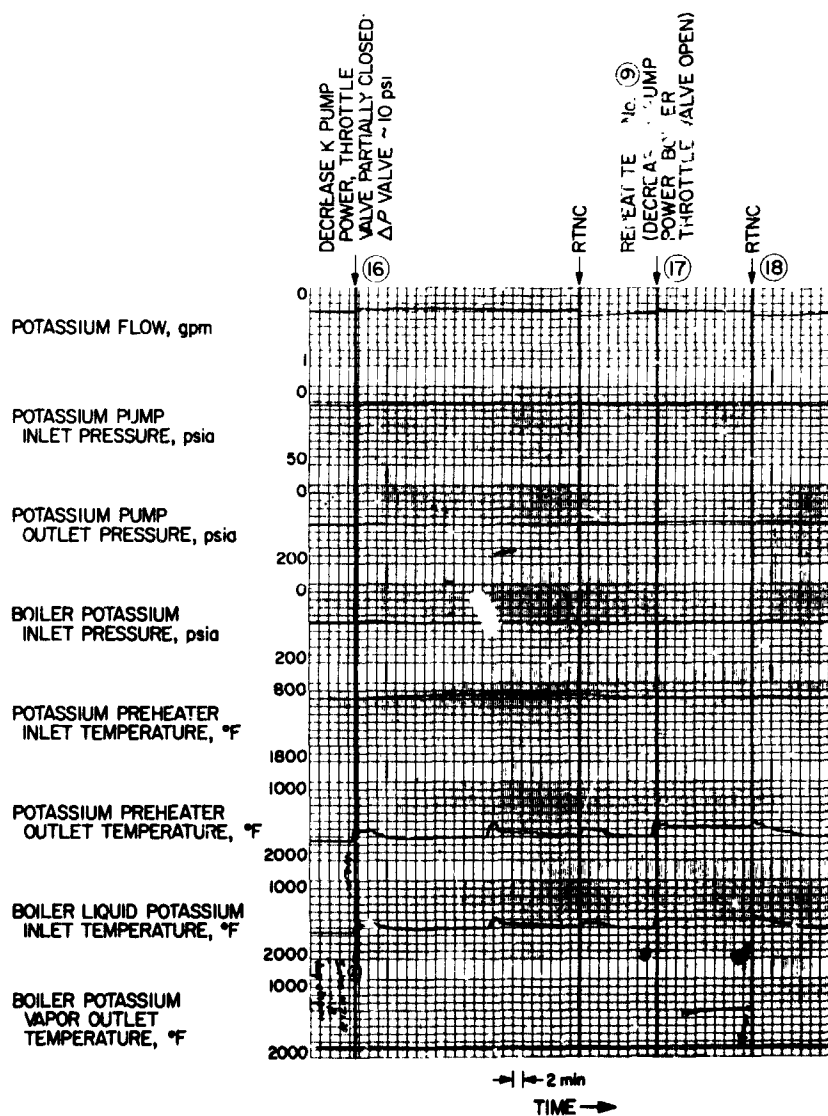


Fig. 31. Sanborn strip-chart recordings: transient tests 15-18

- (4) Return to nominal conditions
- (5) Increase lithium flow ($\Delta \simeq +10\%$)
- (6) Return to nominal conditions
- (7) Increase lithium flow ($\Delta \simeq +20\%$)
- (8) Return to nominal conditions
- (9) Decrease potassium pump power ($\Delta \simeq -10\%$), boiler throttle valve open, manual decrease on K preheater
- (10) Return to nominal conditions
- (11) Increase potassium pump power ($\Delta \simeq +10\%$)
- (12) Decrease potassium pump power ($\Delta \simeq -20\%$) to get to Step 9
- (13) Return to nominal flow
- (14) Increase lithium flow ($\Delta \simeq +37\%$)
- (15) Return to nominal lithium flow
- (16) Decrease potassium pump power as in Step 9 but close throttle valve to give $\Delta P \sim 10$ psi across valve
- (17) Repeat Step 9
- (18) Return to nominal flow
- (19) Decrease potassium pump power as in Step 9 but throttle valve closed more: ΔP valve $\simeq 36$ psi
- (20) Reopen throttle valve
- (21) Scram, lithium power shutoff
- (22) Lithium power on again

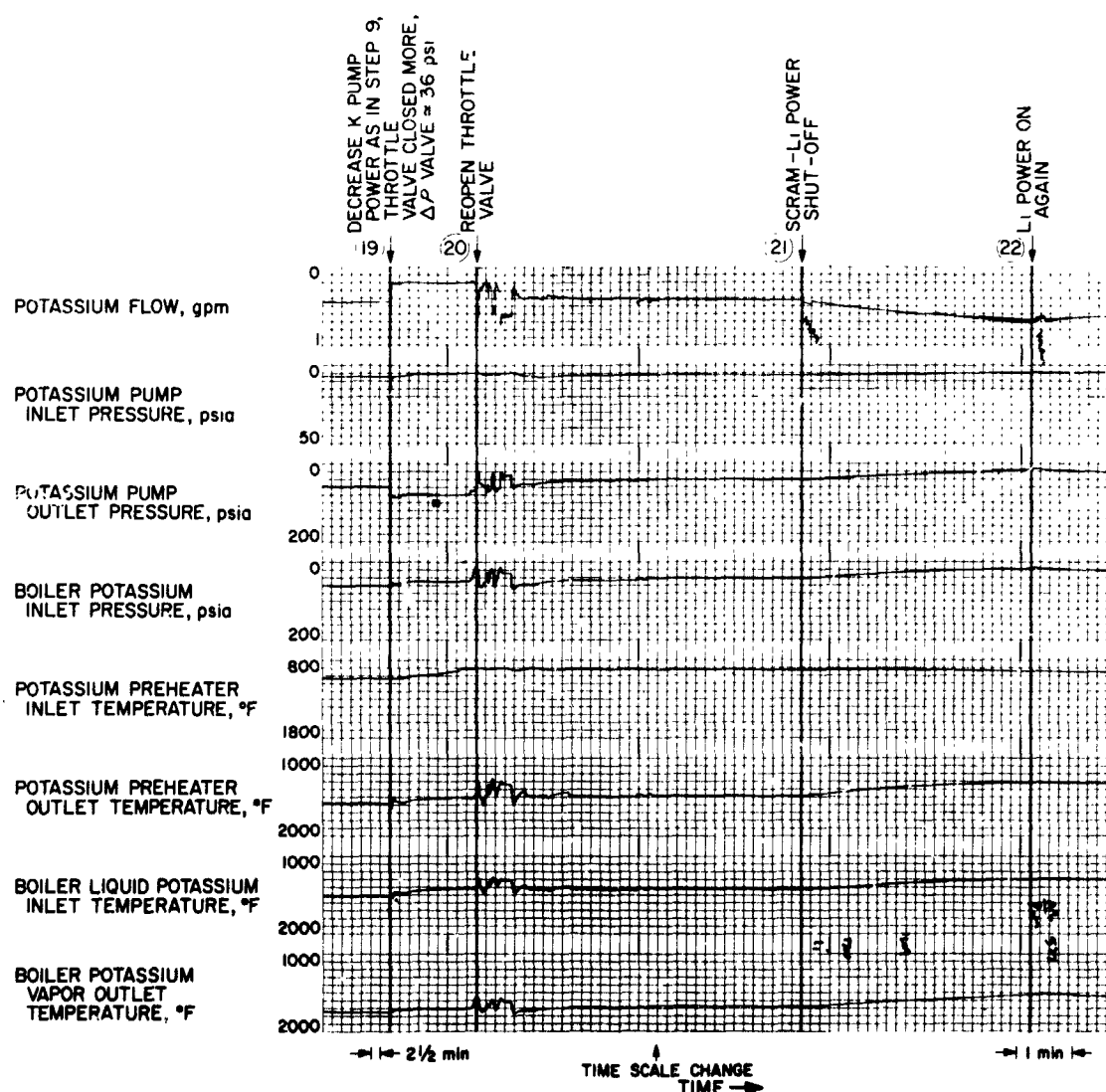


Fig. 32. Sanborn strip-chart recordings: transient tests 19-22

The general conclusion reached following this series of transient loop-behavior tests is that step-change transients of ± 10 to 20% about the operating point in primary flow, secondary flow, power input, and sub-cooling results in smooth transitions to new, stable, operating points.

Boiling test operations were completely shut down in a routine scheduled manner on January 13, 1967, following completion of the initial series of transient tests. Although many attempts were made, operation of the turboalternator was not achieved in spite of the potassium flow, temperature, pressure, and all other pertinent T-A parameters being at their nominal design values. Disassembly and discussion concerning the inoperability of the T-A are presented in Section 3 of this article.

Examination of the loop following the scheduled shutdown revealed small amounts of liquid metal leakage at the bottom of the boiler and at an epoxy-repaired cracked braze-joint on the turboalternator. Analysis of system transient behavior and heat-transfer tests are being carried on and will be reported when completed.

a. Summary of loop operations. Approximately 1000 hr of loop operation were accumulated in this last test period, including ~200 hr of boiling of which 100 hr were at full power (30 kw) and at nominal design temperatures (~1900°F). Approximately 80% of the transient tests have been completed. Those transient tests involving load perturbations were not concluded, as the turbine was inoperable. Over-all loop operation, in general, was very satisfactory. The major conclusions are:

- (1) Drain start is feasible.
- (2) Low-power operation is more unstable than high-power operation due to small magnitude of boiler "pinch-point."²
- (3) High-pressure drop at boiler inlet stabilizes flow but does not necessarily eliminate boiler pressure oscillations.
- (4) Flow-void instabilities (often encountered in natural circulation water boilers) was not observed.
- (5) Flooding-flashing instabilities (not usually encountered in water systems) was the primary instability mode.

²That point in a two-fluid heat exchanger where temperature difference between the two fluids is a minimum.

- (6) High-flow, low-quality boiling is more prone to flooding-flashing instabilities than low-flow, high-quality boiling.
- (7) Boiling "noise" is greater for high-quality flow.
- (8) Response time of Statham and Bourdon pressure transducers is adequately fast.
- (9) Thermocouple locations are critical; 20°F errors can be introduced by small local perturbations.
- (10) Full-power, steady-state operation is extremely stable.
- (11) Step transients $\pm 10\%$ about operating point in primary flow, secondary flow, power input, or sub-cooling result in stable transitions to new operating points.
- (12) Most critical conditions will be startup and low-power operation.
- (13) Programmed start requires intimate knowledge of actual system characteristics (including zero-gravity effects).
- (14) The occurrence of the undesirable phenomenon of boiler flooding-flashing requires the high liquid superheat characteristic of liquid metals. In order to simulate this effect to any degree with water, extremely high purity and very smooth surfaces are required; even then the degree of simulation may not be comparable to liquid metals.
- (15) While not directly concluded from these loop operations, programming potassium flow to heat transferred across the boiler would maintain constant quality or superheat to the turbine which would be highly advantageous to minimize blade erosion.

b. Future goals. The next phase of operations will include: inspection and bench operation of the turboalternator and reinstallation into the test loop; installation of the new cross-flow boiler; and additional full-power loop operations and completion of the transient tests.

2. Loop Disassembly and Cleaning

The lithium-boiling potassium test loop was disassembled following Phase II operations. Both hot traps are to be discarded, a new boiler installed, and the T-A unit is to be opened up for inspection and bench testing. Bolt cutters were used to remove major components from support structures, since new interconnecting piping would have to be fabricated anyway. After this, the loop

components and piping had to be cleaned of residual lithium and potassium.

The liquid metal cleaning operation was accomplished by reacting the liquid metal with Butyl Cellosolve.³ This reactant was chosen for two reasons: primarily, because it is the only reactant known that reacts with a liquid metal in a Cb-I-Zr component without hydriding the columbium; secondly, it appears to be less likely to flash than the reactant normally used on noncolumbium parts (alcohol-kerosene mixture). The reaction rate appears slightly slower than with butyl alcohol. In all component cleaning, the volume of fluid was kept large enough to prevent the bulk temperature from rising appreciably. When cleaning the radiator-condenser coils and the potassium pump, the Butyl Cellosolve was recirculatively pumped through these components to prevent the temperature from rising excessively. After complete reaction between the Butyl Cellosolve and liquid metal had occurred, the parts were then cleaned in alcohol and water rinsed. This method of cleanup of liquid-metal-contaminated components proved to be very effective. Components and portions of the loop to be used again were also pickled to remove any surface contamination.

3. Preliminary Results of Turboalternator Inspection Following Disassembly

At no time during testing were there any indications that the T-A was rotating. Rotation is indicated by alternator output frequency. A decision was made to disassemble the unit for inspection to determine the cause of seizure. After disassembly and cleaning, running clearances of bearings, shaft, wheel and rotor, and the concentricity and parallelism of flanges and mounting faces were determined.

Two items were discovered in the inspection that could give rise to conditions that would prevent rotation of the unit:

- (1) The mounting surfaces for the two bearing assembly flanges were out of parallel by 0.015 in. at about the diameter of 5 in. This is equivalent to an angular misalignment of $0^{\circ}10'$, which is sufficient to prevent rotation of the shaft.
- (2) There was inadequate end clearance between the bore of the alternator case and that portion of

³Glycol-monobutyl-ether. "Butyl Cellosolve," tradename by Union Carbide Corp.

the rotating assembly between the thrust bearing and the rotor. Measurements indicate this clearance to be 0.010 in. at room temperature. This clearance might become an interference at operating temperatures depending on the pessimism of assumptions made regarding temperature gradients. If the clearance was decreased by more than the 0.010 in., the thrust washer would be pressed into intimate contact with the mating portion of the slightly (1°) conical thrust-bearing pads. Photographs of these two surfaces are shown in Fig. 33. The metal transported from one surface to the other indicates that high temperatures and/or pressures were experienced prior to disassembly.

4. Metallurgical Examination of Loop

Metallographic samples have been taken from both loops and are presently undergoing evaluation. Preliminary photos and observations are presented in the following section to indicate the trends observed. A final report on observations will be prepared when metallography and chemical analyses are completed.

Minimal corrosive effects were observed in both loops of the system. A photo of the inner surface of the liquid portion of the potassium loop is presented in Fig. 34. The drawing marks present on the surface are typical of both the as-received tubing as well as almost all of the samples taken from the loop. No evidence of corrosion was detectable in this sample.

The zirconium hot trap used in the liquid portion of the potassium loop is shown in Fig. 35. The inner surface plainly showed the machining marks from fabrication. Discoloration is believed to be a result of the Butyl Cellosolve cleaning agent used to react with the potassium present in the component. No evidence of corrosion was observed during metallographic examination of sections taken from the hot trap.

Changes in the appearance of the surface, however, were detected in the vapor portion of the potassium system. The drawing marks typical of as-received tubing were less prominent, and the surface had a roughened appearance. A section of this potassium turbine vapor by-pass line is shown in Fig. 36. The roughness shown is considerably greater than any detected in any other portion of the loop. Since no preferential attack was observable, this roughening may be a result of erosion by liquid droplets entrained in the potassium vapor.

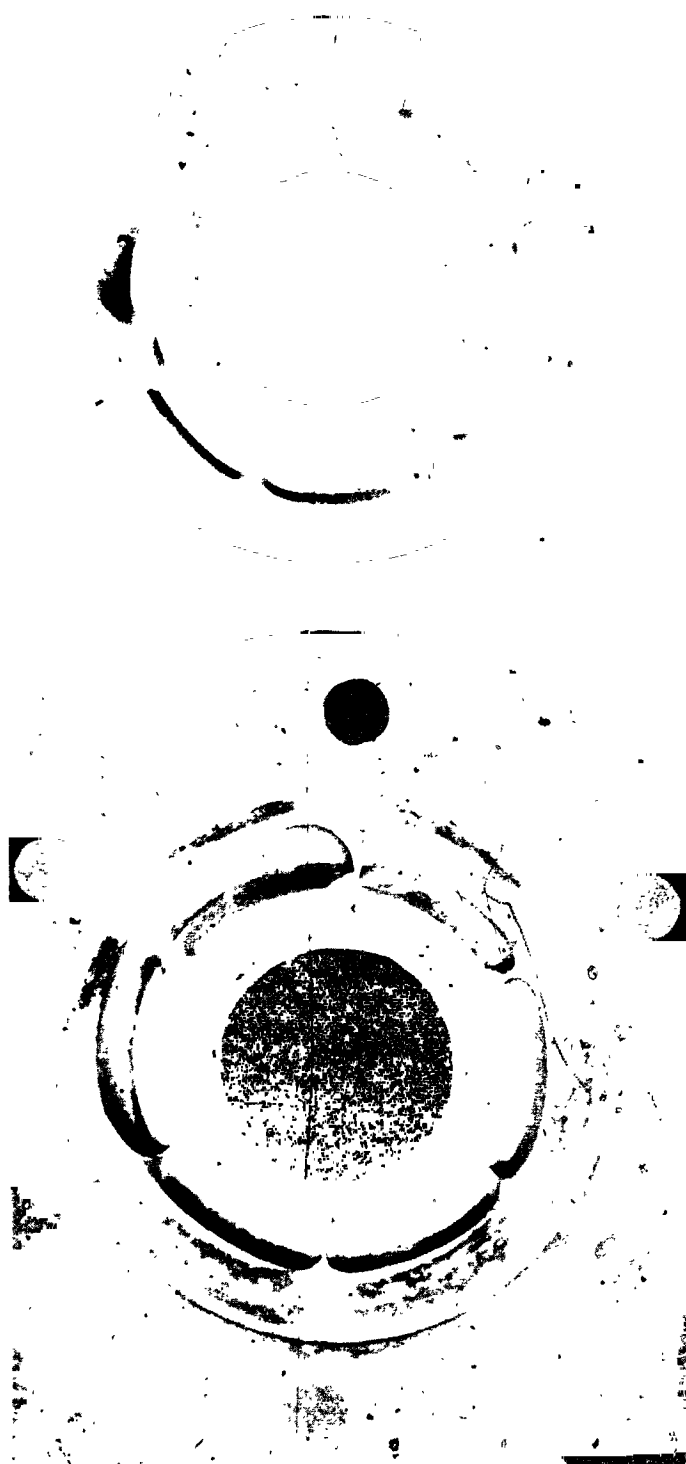


**Fig. 33. Turboalternator thrust bearing pads
after disassembly**



**Fig. 34. Potassium system liquid line,
inner surface (14 X)**

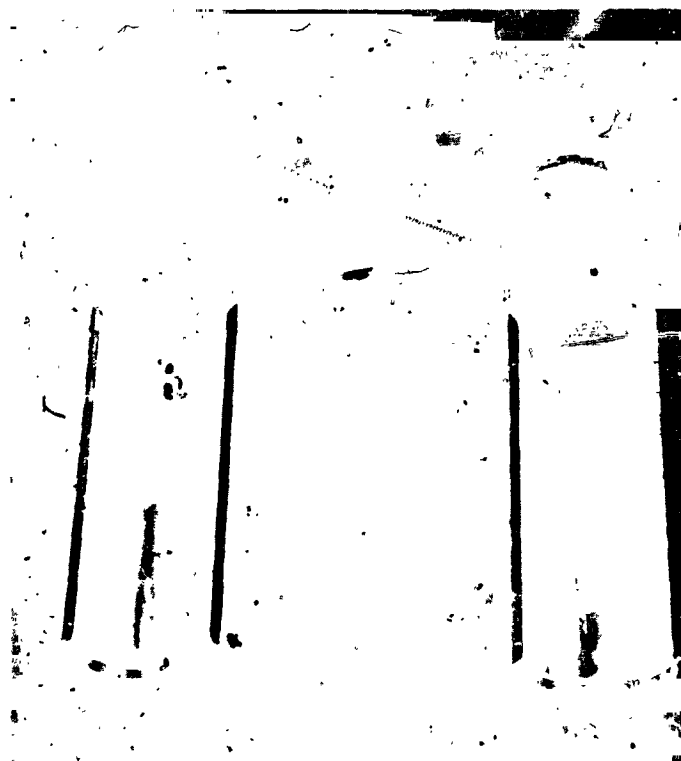


Fig. 35. Potassium hot trap (zirconium getter)

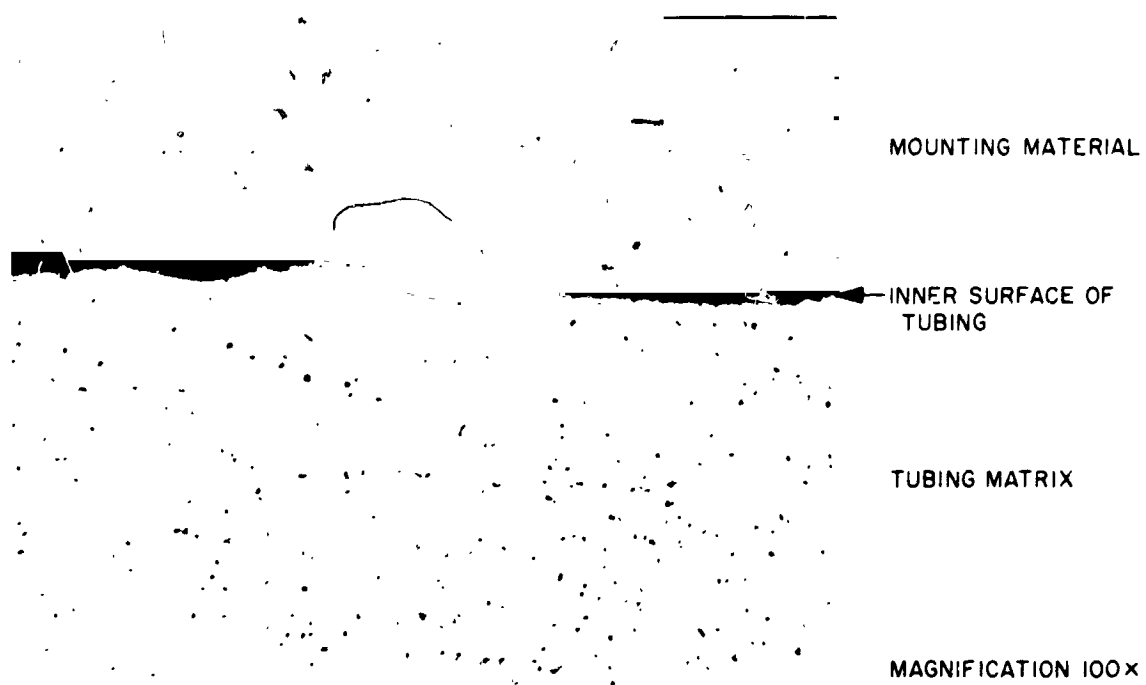


Fig. 36. Inner surface of potassium turbine vapor by-pass line, metallographic section (100 X)

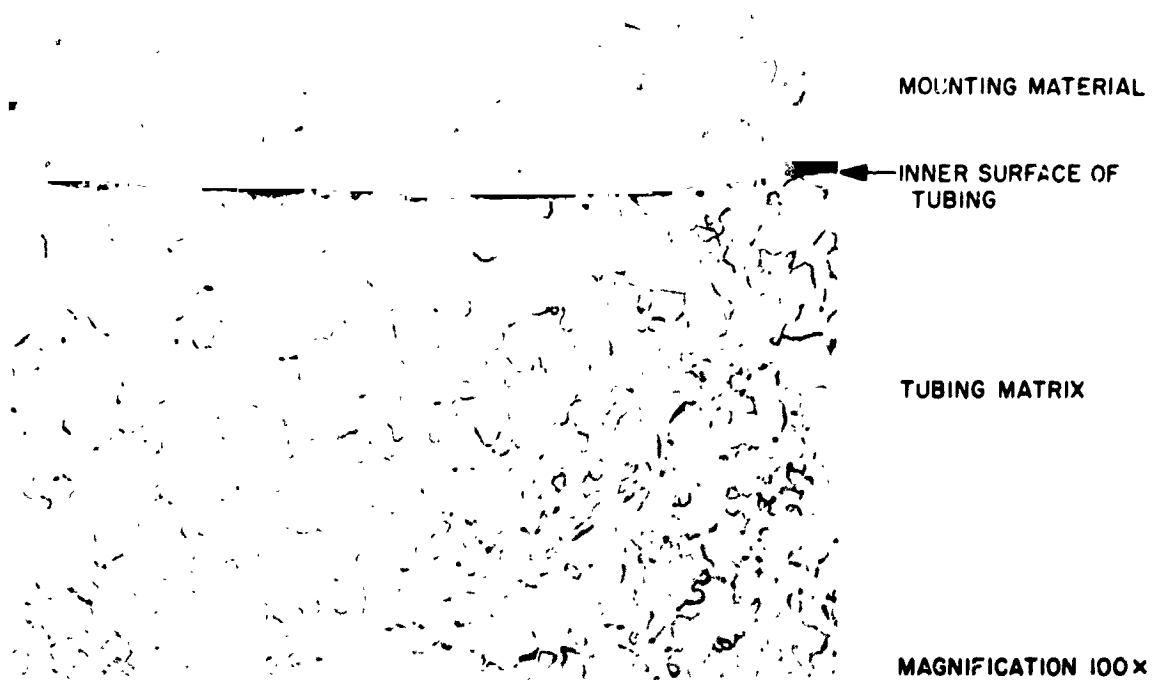


Fig. 37. Inner surface of lithium primary heater coil outlet, metallographic section (100 X)

Tubing sections taken from the boiler display the characteristic drawing marks, as well as light scratches incurred during boiler assembly. Metallographic examination of sections taken from the centerless ground tube, which was the heat-exchange surface between the lithium and the potassium, showed no corrosive effects.

Sections taken from the inlet of the primary lithium heater coil (the coldest spot in the lithium loop) displayed neither corrosive nor mass-transfer effects. The surface of the outlet of the lithium heater coil (hottest part of the loop) retained the characteristic drawing marks; however, some roughening was visible, indicating etching or solution corrosion of this area. This effect was slight, as indicated by the metallographic section (Fig. 37) which displayed very minimal preferential etching of the grain boundaries.

Hot trapping of oxygen in the lithium loop was done with yttrium. The yttrium element was intact after sectioning of the hot trap; however, disintegration took place during the cleaning operation during which the lithium reacted with Butyl-Cellosolve (Fig. 38). Oxygen analyses of the lithium after test indicated 700 ppm, which would allow considerable gettering of oxygen

by the yttrium. Small particles of yttrium were found in one low spot of the loop, indicating chipping of the yttrium getter element, presumably due to embrittlement produced by oxygen pick-up during operation. No evidence of mass transfer of yttrium could be found in any portion of the loop.

a. Chemical analysis results. Sections of both loops were submitted for chemical analysis, as well as samples of the liquid metals. While the results are not yet complete, the available data are presented in Table 2.

Two effects are prominent in these data. The first is depletion of oxygen from the outer surface of the potassium system tubing. This can be attributed to partitioning of oxygen between the tubing and the zirconium foil. The second effect is an increase in hydrogen on the outer surfaces of the potassium system tubing. This is attributed to a small leak of organic coolant which developed during initial loop startup and was subsequently corrected.

An increase is indicated in the carbon concentration at the inner surface of the lithium system tubing. Duplicate samples have been submitted to determine if this is a true effect, and samples from the hot portion of the loop have been submitted for analysis to determine if a carbon depletion exists in that area.



Fig. 38. Lithium hot trap (yttrium getter disintegrated during post-test liquid metal cleaning operation)

Table 2. Analyses of columbium-zirconium alloys

	Element, ppm				
	C	H	O	N	Zr
Typical as-received tubing	50	5	250	50	9000
Potassium vapor tubing					
OD	55	84	50	140	8800
Core	23	17	210	160	9400
ID	23	18	340	160	9000
Lithium system tubing from boiler outlet (cool leg of system)					
OD	46	*	740	540	9000
Core	26	*	690	350	9000
ID	259	*	650	150	10100
Lithium, after operation	—	*	700	—	—
* These samples were cleaned in water to determine extent of hydrogen pick-up. Typical numbers were 500 ppm.					

D. Plasma Studies in the Electron Bombardment Ion Engine—Magnetic Field Effects, T. D. Masek

1. Introduction

This report is part of a continuing study of the plasma in the electron bombardment engine. A previous report (SPS 37-42, Vol. IV, pp. 131-137) discussed the general effects of arc current and voltage on the electron energy distribution function. It was shown that the arc current, by changing the electron-neutral density ratio, significantly affected the high-energy region of the energy distribution. These data were reported for a single magnetic field strength. It is also of interest to study the variation of plasma characteristics with changes in magnetic field magnitude. The present report describes the observed effects of magnetic field strength on the electron energy distribution function for several propellant flowrates and arc conditions.

2. Plasma Measurements

The data presented in this report were taken during the same mercury engine experiments as described above. Thus, the experimental set-up will not be discussed again. As before, the probe positions were 0.65 in. apart axially, beginning 0.18 in. from the screen grid, and were 0.25 in. apart radially, starting 0.50 in. off center. All data are plotted in normalized coordinates.

The axial magnetic field strength is plotted in Fig. 39. This is the nonoperating field and is undoubtedly af-

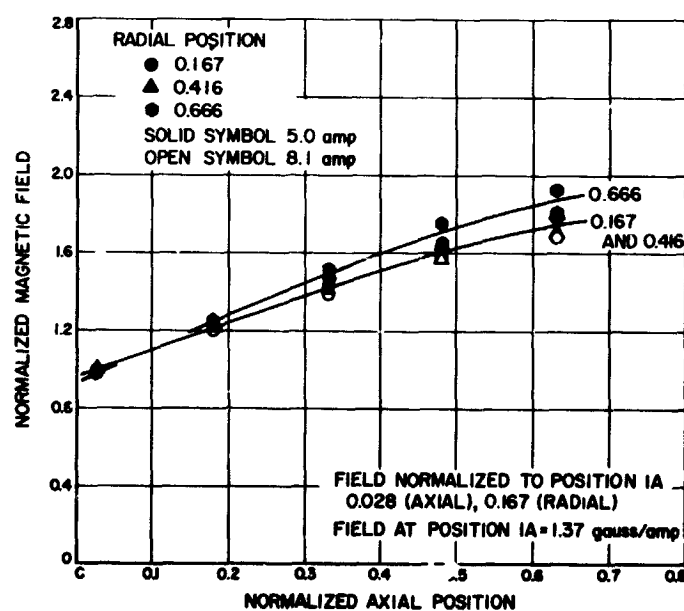


Fig. 39. Axial magnetic field distribution

fected to some extent by the plasma. Although the field lines are somewhat divergent, relative changes in the plasma characteristics can be related to changes in the externally applied field.

Semilogarithmic plots of several Langmuir probe traces are shown in Figs. 40 and 41. This data was obtained at the most central grid position (0.042, 0.167) and with constant arc current. The propellant flowrates, beam currents, and arc voltages are indicated in the figures. The plasma characteristics, ion density, electron temperature and plasma potential, determined from this data are shown in Figs. 42 to 44. The additional data points shown in Figs. 42 to 44 were obtained from plots similar to Figs. 40 and 41.

It is important to note that although many of the semilogarithmic curves are straight lines to the left of the "knee" for less than an order of magnitude in probe current, all data has been reduced on the basis of these straight lines. This should be a reasonable procedure in light of the discussion in SPS 37-42, Vol. IV. (That is, the electron energy distribution for high arc currents, 10 to 14 amp, appears to be approximately a Maxwellian distribution disturbed by high-energy electron gain or loss.) The reasoning behind the selection of these straight lines and the mechanisms causing the shifts in distribution will be presented in the following discussion.

a. Distribution function variations. In studying Figs. 40 and 41, it is readily apparent that the electron energy distribution significantly changes its nature between magnet currents of 5 and 9 amp. The distribution is one of excess high-energy electrons at low magnet currents but gradually changes to one lacking high-energy electrons at higher currents. This is indicated by the fact that the data falls above the Maxwellian line for negative probe voltages at low magnet currents but lies below the Maxwellian line at higher currents. This trend persists throughout the data for all flowrates. At lower arc currents the data tend toward the excess electron nature indicated in SPS 37-42, Vol. IV.

The mechanism producing the change in the distribution function can be explained as follows. First, it is necessary to recognize that the axially applied magnetic field traps radially directed electrons in circular orbits. This trapping in general restricts the radial flow of electrons. Thus, radial electron flow depends on collisions of electrons with other particles. However, electrons can move freely axially. This axial freedom allows most electrons to reach one or both ends of the engine housing.

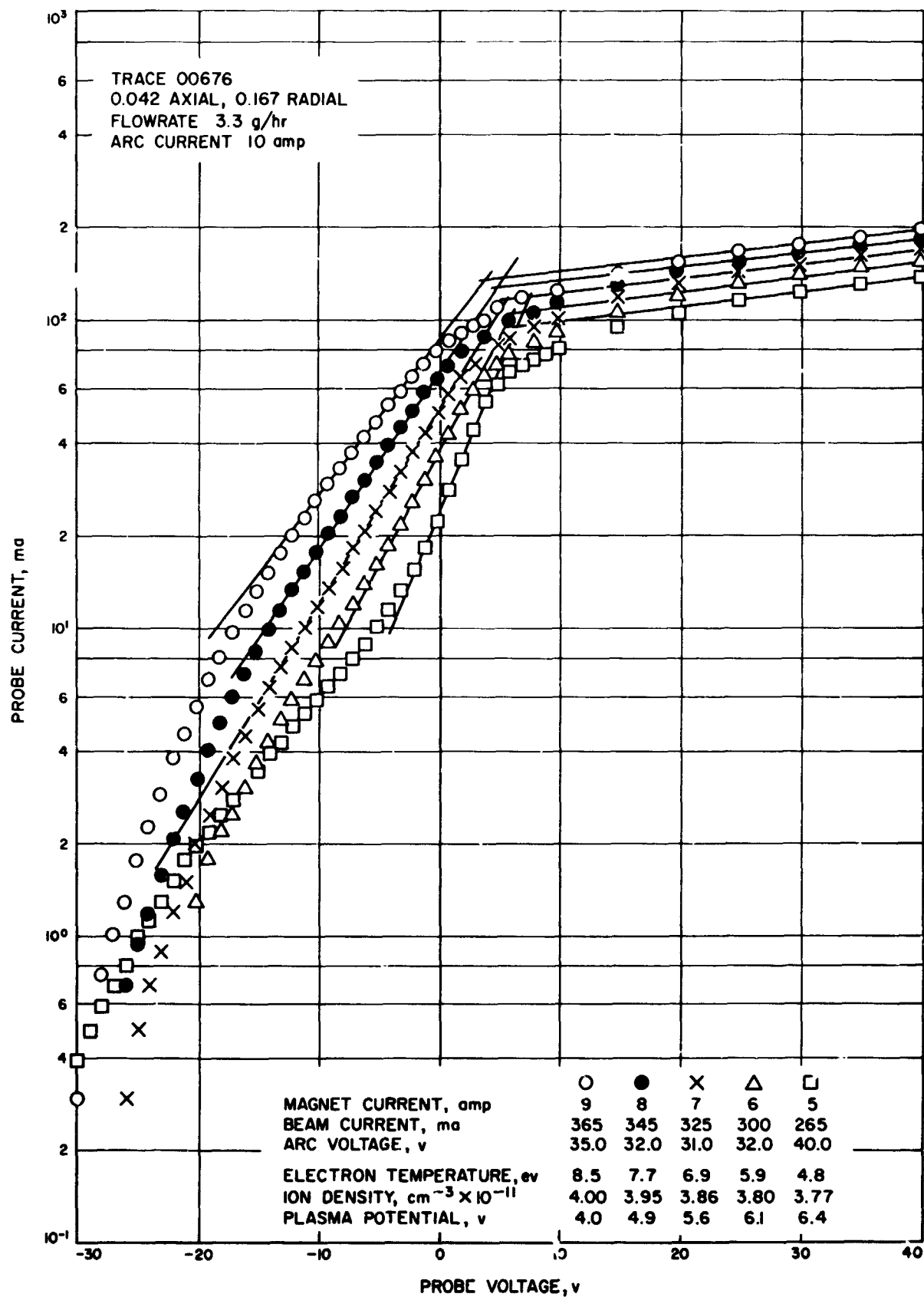


Fig. 40. Semilogarithmic plot of Langmuir probe data with variable magnetic field, 3.3 g/hr

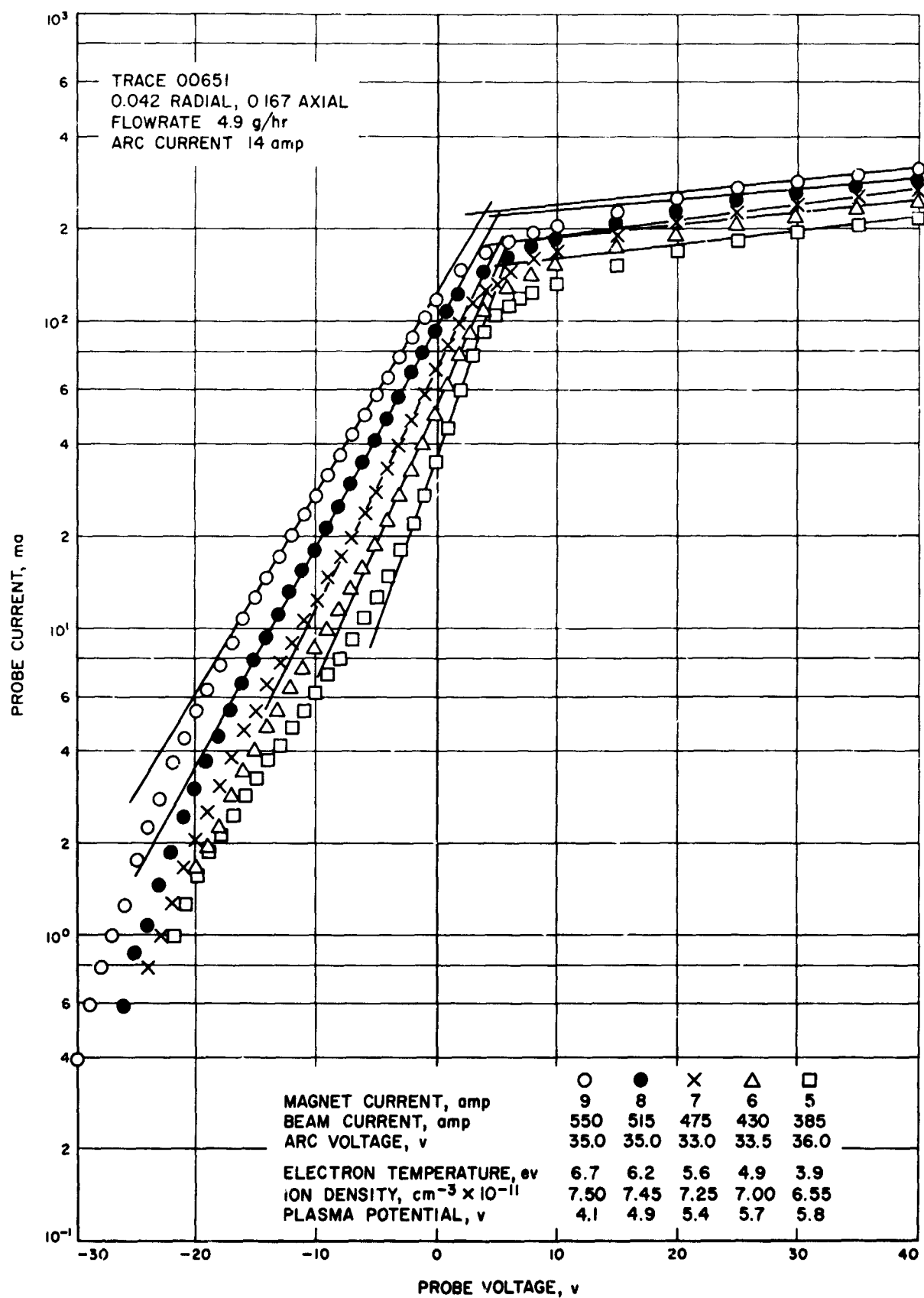


Fig. 41. Semilogarithmic plot of Langmuir probe data with variable magnetic field, 4.9 g/hr

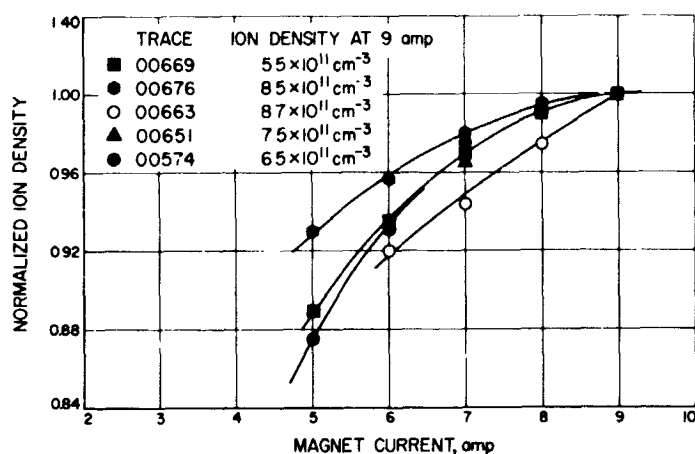


Fig. 42. Normalized ion density variation with magnetic field strength

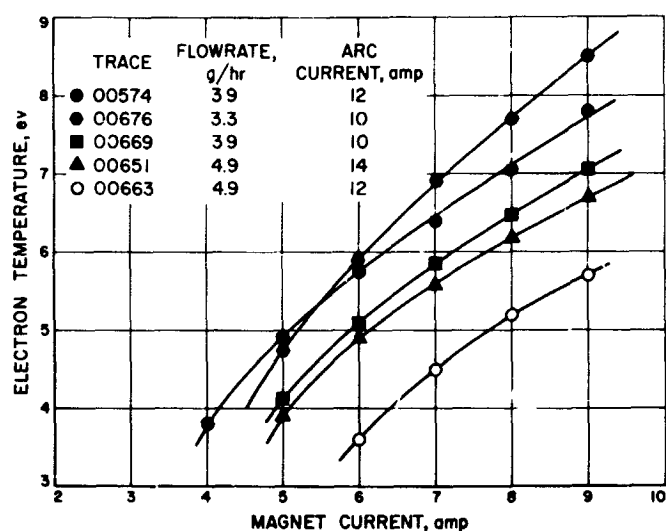


Fig. 43. Maxwellian electron temperature variation with magnetic field strength

Once trapped by the magnetic field, electrons can travel only radially by colliding with another particle (an electron, ion, or neutral atom). The rate of electron flow across the chamber, cathode to anode, is thus determined by the highest collision frequency and by the magnetic field strength. Since the electrons move approximately one cyclotron radius per collision, the higher the axial magnetic field the more collisions required to reach the anode. This indicates that the degree to which the electrons approximate a Maxwellian distribution (determined by electron-electron collisions) and the degree of ionization (determined by electron-neutral collisions) depend on the axial magnetic field strength.

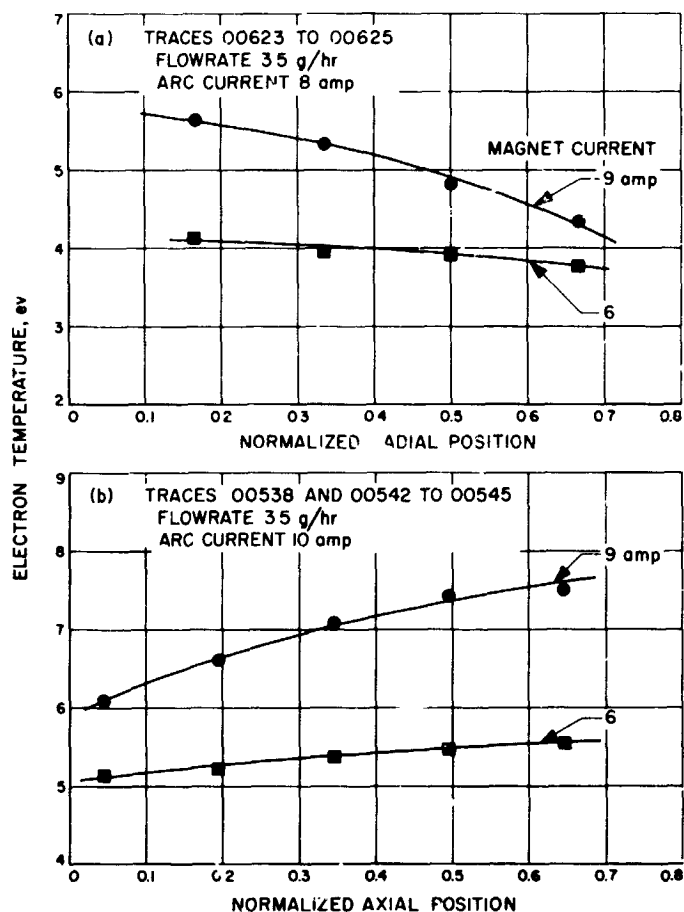


Fig. 44. Maxwellian electron temperature at two magnetic field strengths (a) radial variation; (b) axial variation

Of most significance in discussing the electrons is a distinction between two possible electron groups. Electrons emitted from the cathode, termed primary electrons, initially have energies equal to the sum of the arc voltage and the plasma potential (on the order of 40 eV in the present case). The second electron group is of lower energy, 4 to 10 eV, and is formed by electrons produced in ionization and in primary electron inelastic collisions. The rate at which primary electrons transfer their energy to neutrals, ions, and other electrons determines the total energy distribution among all the electrons. Therefore, the relaxation time for primary electrons is important and must be compared with the time required for high-energy electrons to traverse the chamber radius.

The various collision times and the primary electron relaxation time were summarized in Ref. 9. The time required for 40 eV electrons to relax into a Maxwellian distribution of about 7 eV with an electron density of $5 \times 10^{11} \text{ cm}^{-3}$ is shown to be approximately $1.8 \times 10^{-8} \text{ sec}$.

The primary electron-ion or primary electron-Maxwell electron collision time is about 6×10^{-6} sec. The primary-neutral times are about 3×10^{-6} for elastic collisions and 8×10^{-6} for inelastic collisions for a neutral density of $5 \times 10^{11} \text{ cm}^{-3}$. Since the ion-neutral ratio changes across the chamber, and since a neutral density of $5 \times 10^{11} \text{ cm}^{-3}$ is probably a good average, 3×10^{-6} sec will be used as the average scattering collision time.

With an average magnetic field of 20 gauss, the cyclotron radius of 40 ev electrons is about 1.1 cm. The chamber radius is about 7.5 cm, so that a 40-ev electron requires about seven collisions to reach the anode. These seven collisions require, using the previous collision time, approximately 2×10^{-5} sec, or about the same time as for primary relaxation.

However, as the magnetic field is reduced, two effects occur. First, the cyclotron radius increases, thereby reducing the number of collisions required to reach the anode. Second, less energy is transferred to the lower energy electron group, reducing the group energy. Using a Maxwellian energy of 5 ev and a field of 11 gauss (Fig. 41), the relaxation time is about 2.2×10^{-5} sec, and the time required for 40 ev electrons to traverse the chamber is about 1.2×10^{-5} sec. Thus, these electrons escape in about half the time required for relaxation.

The previous collision time comparisons, in part, provide the explanation for the distribution function changes with magnetic field changes found experimentally. However, an additional consideration, relating to high-energy electron loss previously discussed, is also required to complete the explanation. At high magnetic fields, and with high arc currents (SPS 37-42, Vol. IV), the distribution lacks high-energy electrons relative to a Maxwellian distribution as seen in Figs. 40 and 41. Electrons with energies greater than the cathode sheath potential (40 ev in the present example) can overcome this barrier at the housing and escape to neutralize ions which also diffuse to the housing. Although only the portion of electrons with energy greater than this sheath potential can escape to the housing, some electrons from the lower energies will increase in energy through collisions to fill in the energy gap. This causes the data to decrease continuously and to begin decreasing at energies below 40 ev.

The mechanisms for changing the distribution function with magnetic field changes can now be clarified. At high fields, most of the primary electrons relax into a basically Maxwellian distribution before reaching the anode because of the number of collisions required to traverse the

chamber. The loss mechanism discussed in the last paragraph for high-energy electrons causes the distribution to lack these electrons relative to a normal Maxwellian distribution. As the field is reduced, the number of collisions required for electrons to reach the anode is reduced. This reduces the number joining the Maxwellian group and leaves an excess of high-energy primary electrons relative to the Maxwellian distribution indicated by the straight lines through the data. It is expected that the primary group is not monoenergetic, because the electrons have at least a few collisions before reaching the anode. The exact form of this high-energy distribution will be discussed later in this series of reports.

b. Plasma characteristics variations. With the previous discussion for reference, the electron temperature, ion density, and plasma potential variations with magnetic field can be considered. These characteristics will also be discussed in terms of relative field changes. It is clear from Figs. 42, 43, and 45 that electron temperature and ion density are directly proportional to a function of the magnetic field while the plasma potential varies inversely with field.

The electron temperature curves shift upward consistently with reducing flowrate and increasing arc current. This corresponds to increasing propellant utilization efficiency. A similar upward shift occurs in the normalized ion density curves, although not quite so consistently. The plasma potential curves do not shift consistently. This can probably be attributed to the differences in arc voltage and the data reduction technique

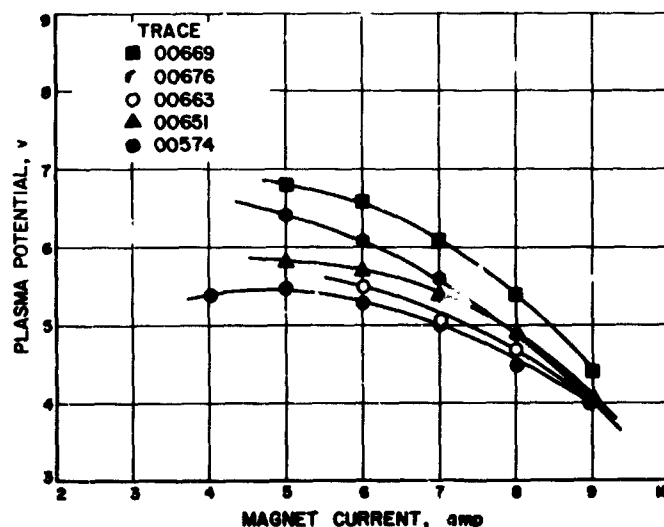


Fig. 45. Plasma potential temperature variation with magnetic field strength

utilizing the low-energy Maxwellian lines. However, the variation of plasma potential with field is quite consistent.

Considering any initial magnet current, a reduction in this current reduces the Maxwellian electron temperature because of the reduced energy transfer from the primary electron group. This decrease is apparent in Fig. 43. An additional effect to be expected in this regard is an improvement in electron temperature uniformity spacially with reducing magnetic field. An example of this improvement is shown in Fig. 44. The semilogarithmic plot of the data for these is not included for brevity. The figures show that high-energy electrons distribute their energy more uniformly at lower magnetic fields, since the trapping effect is reduced.

The plasma potential represents the ability of electrons to diffuse away from the ions and form a net space charge. Although the electron energy drops significantly with magnetic field, the velocity drops as the square root of the energy. At the same time, the distance electrons can move radially changes inversely with the field. The high magnet current portions of Fig. 43 indicate curve slopes of about 0.5 to 0.8 eV/amp, and the corresponding curves in Fig. 45 have slopes of about 1 v/amp. At low currents these slopes are about 1.0 to 1.5 eV/amp and

0.1 to 0.3 v/amp. This indicates that a lower magnetic field allows electrons to diffuse more rapidly, causing the plasma potential to increase. But the electron energy decrease partially compensates for this freedom and tends to slow the plasma potential increase. The data from trace 00574 in Fig. 44(a) actually begins to decrease, reflecting the compensating effect. In addition, the primary electron flow increase at the anode caused by the reduced field reduces the number of Maxwell electrons reaching the anode for a given arc current. This tends to increase the anode sheath potential since the sheath changes to reduce the flow of lower energy electrons. This sheath increase also tends to shift the plasma potential.

3. Conclusions

At the present time, a method for predicting the magnitude or variations of the previously discussed characteristics is not available. It is believed that the insight gained in basic studies described here and in SPS 37-42, Vol. IV will aid in formulating such a method.

Additional data must be analyzed to verify the trends reported here. Data obtained in a conical engine operated with both mercury and cesium will be used for this purpose. The basic information gained in these studies should greatly aid in engine design and optimization.

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